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A Transdisciplinary Approach to Decision Support for Dams in the Northeastern U.S. with Hydropower Potential

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A TRANSDISCIPLINARY APPROACH TO DECISION SUPPORT FOR DAMS IN THE NORTHEASTERN U.S. WITH HYDROPOWER POTENTIAL

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By Emma Fox

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An Abstract of the Dissertation Presented
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The Federal Energy Regulatory Commission (FERC) is the regulatory body that oversees non-federally owned dam operations in the United States. With more than 300 hydropower dams across the U.S. seeking FERC relicense between 2020 and 2029, and 135 of those dams within the Northeast region alone, it is prudent to anticipate and plan for such decision-making processes. Anyone may be involved in FERC relicensing; in fact, FERC solicits public comment and requires the licensee to hold a public hearing during the process. Parties may also elect to apply for legal intervenor status, allowing them a more formal entry into the relicensing process. However, there are two key barriers that may keep the public from participating in a dam decision making process in an impactful way. The first of these barriers is *access to information*. Having access to the types of information that matters to FERC is important, because it allows the participant to communicate their support or concerns about the relicensing using the language of the process. In particular, participants other than the licensee may not have access to project economic information, so this is a focus in my research. The second barrier is *capacity to participate* in a way that impacts the process (i.e., institutional knowledge about what kinds of decision criteria (factors) and decision alternatives (project options), as well as relevant data, that FERC typically weighs in their decision making or has considered in the past). Actors not privy to license information (perhaps encountering difficulty in navigating the FERC eLibrary), lacking knowledge of FERC process conventions, or otherwise unfamiliar with hydropower dam schemes or operations have substantial hurdles preventing their effective participation. My research, situated in the sustainability science arena, addresses hydropower project cost

and performance assessment and multi-criteria considerations for dam decision support. I lead the development and assessment of an online Dam Decision Support Tool aimed at addressing barriers to the hydropower dam decision-making process. My work demonstrates possibilities for tailoring decision tools to incorporate stakeholder perspectives into decision making about hydropower dams.

DEDICATION

To my husband, who followed me to Maine, supported me during my graduate school journey, and still loves me (somehow). To my family and friends, I am deeply grateful for your patience, understanding, and diligence in checking up on me, especially during the last few months. I often joked that if I once walked from Maine to Virginia on the Appalachian Trail, then I could write a dissertation, no problem. This was much harder.

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SHP – Small-scale hydropower

USDOE – U.S. Department of Energy

USACE – U.S. Army Corps of Engineers

USBR – U.S. Bureau of Reclamation

USGS – U.S. Geological Survey

NREL – National Renewable Energy Laboratory

ONRL – Oak Ridge National Laboratory

INL – Idaho National Laboratory

PNNL **-** Pacific Northwest National Laboratory

FERC – Federal Energy Regulatory Commission

IRENA – International Renewable Energy Agency

NWRED – Norwegian Water Resources and Energy Directorate

NRC – Natural Resources Canada

HEEA **-** Hydropower Energy and Economic Assessment

EIA – Energy Information Administration

WEAP – Water Evaluation and Planning system

ASD-PSO – Adaptive Search Diversification and Particle Swarm Optimization

NPD – Non-powered dam

NSD – New stream-reach development

ROR – Run-of-river hydropower

PS – Pumped storage hydropower

NPV – Net present value

BCR – Benefit-cost ratio

IRR – Initial rate of return

LCOE – Levelized cost of energy

C_{CAP} – Capital cost

O&M – Operations and maintenance

USD – U.S. Dollars ($)

EUR – Euros (€)

INR – Indian Rupee

GBP – Great British Pound sterling

MYR – Malaysian Ringgit

REC – Renewable Energy Credit

NID – National Inventory of Dams

HKT – Hydrokinetic

PV – Solar photovoltaics

BT – Battery

DG – Diesel generator

SAR – Store-and-release

CO_2 – Carbon dioxide

GHG – Greenhouse Gas

FERC – Federal Energy Regulatory Commission

NOAA – National Oceanic and Atmospheric Administration

LIHI – Low-Impact Hydropower Institute

FPA -Federal Power Act

ESA – Endangered Species Act

NPC – Net present costs

NPB – Net present benefits

NPB_{soc} – Social net present benefits

NPV_{soc} – Social net present value

MCDA- Multi-Criteria Decision Analysis

DM – Decision Maker

AHP – Analytical Hierarchy Process

MAUT – Multi-Attribute Utility Theory

MAVT – Multi-Attribute Value Theory

WS – Weighted Sum

TOPSIS – Technique Ordering Preferences by Similarity to Ideal Solutions

ELECTRE – ELection Et Choix Traduisant la REalité

PROMETHEE – Preference Ranking Organization Method for Enrichment Evaluations

NAIADE – Novel Approach to Imprecise Assessment and Decision Environments

DAI – Decision Analysis Interview

SBSE – Scenario-Based Stakeholder Engagement

SMCE – Social Multi-Criteria Evaluation

SMART – Simple Multi-Attribute Rating Technique

SWING – Simple weighting technique, acronym never spelled in source

MOA – Multi-Objective Algorithm

CPSS – Collaborative Planning Support System

SDS – System Dynamics Simulation

IDAM – Interdisciplinary Dam Assessment Model

SIMADA – SImulation-based Multi-Attribute Decision Analysis

PERSEUS-NET – Power systems analysis software, acronym never spelled in source

HIPRE – Decision support software for MAVT and AHP, acronym never spelled in source

ESDF – Evolutionary Systems Design Framework

DM – Decision Maker

NSF – National Science Foundation

EPSCoR – Established Program to Stimulate Competitive Research

SMCE – Social Multi-Criteria Evaluation

MOGA – Multi-Objective Genetic Algorithm

PRRP – Penobscot River Restoration Project

DDST – Dam Decision Support Tool

UI – User Interface

UX – User Experience

FOD – Future of Dams

1.0. STAKEHOLDER PARTICIPATION IN PROBLEM-DRIVEN DECISION SUPPORT FOR DAMS RESEARCH

Abstract

Hydroelectric dams present sustainability challenges not easily disentangled from their benefits to the electricity grid. More than 300 Federal Energy Regulatory Commission (FERC) hydropower license applications are expected in the next 10 years across the U.S., with 45 percent of those projects in the Northeastern region. Relicense applications are often submitted with project changes, so relicensing presents a key opportunity to evaluate the negative impacts of a dam (e.g., an impediment to migratory fish) against the benefits it provides (e.g., renewable electricity generation), to determine the best possible future for the site (e.g., business-as-usual, fish passage, improvements, hydropower generation improvements, removal). With so many relicensing applications anticipated in the Northeast, the time is right to plan for supporting stakeholder participation in relicensing, a process open to public comment. My research examines the cost and benefits of hydropower generation and engages stakeholders in the development of a Dam Decision Support Tool aimed at lowering barriers to participation in the FERC relicensing process.

Keywords: stakeholder engagement, small-scale hydropower, sustainability science, decision support, multi-criteria decision analysis

1.1. Introduction

Hydropower is a valuable renewable energy technology, particularly due to the grid-support services it provides; e.g., load-following generation, storage, and baseload generation [1], [2]. The first U.S. hydropower dam was installed in Wisconsin’s Fox River in 1882 [1], preceding a national wave of development from the 1900s – 1930s (new construction in previously free-flowing rivers), and a second wave of development (mostly retrofits on existing dam infrastructure) from the 1980s into the 1990s [3]. The U.S. now generates 7 percent of its electricity from hydropower [3]–[5], which remains the largest source of renewable energy for the nation, with a cumulative conventional (i.e., excluding pumped storage powerplants) project power capacity of 78 GW [1]. As of 2006, most (49%, or 1179 power plants) of the conventional hydropower plants in the U.S. fleet (2388 total) can be categorized as small-to-medium scale (i.e., 1 – 30 MW, see Ch. 3) [4].

Internationally, dam construction is increasing as small-scale hydropower (SHP, <10 MW [1], [4]) expands rapidly as a source of renewable electricity [5]. Smith et al. [6] estimate that SHP has an estimated potential (cumulative, uninstalled additional) capacity of 173 GW across the globe. Smith et al. suggest that the U.S., whose SHP market is considered mature by global standards, also has room to grow, where developers take advantage of existing low-head and conduit infrastructure. To that effect, many recent U.S. studies have reviewed the technical potential for additional hydropower capacity [7]–[10]. Despite government interest in the feasibility of additional development (i.e., recent studies from Oak Ridge National Laboratory [11]–[13]), hydropower is hardly the only solution in the transition away from fossil fuels, particularly because so many smaller project operations still fluctuate seasonally (due to their 'run-of-river' designs that maintain minimum flows) [14], threaten migrating fish stocks (see, for instance, Magilligan et al. [15]), and meet intense public opposition [16], [17]. Hydropower's reputation has come under fire in the last decade as a source of energy, and its importance in the domestic energy mix seems to be on the decline [3]. Contributing to this decline is an increase in dam removals, especially in New England, where removals have contributed to restoring migratory routes for endangered fish species [18], or balanced removal with improvements to fish passage and increased power capacity [19], evidencing possibilities for more strategic evaluation of hydropower assets on a multi-dam scale.

I am interested in the economic sustainability of business-as-usual hydropower project operations, as well as the other kinds of decision alternatives that owners and dam stakeholders consider in Federal Energy Regulatory Commission (FERC) relicensing (e.g., dam removal and improvements to fish passage facilities). My work is motivated by the challenges facing the Northeast region (particularly Maine), where many aging and privately-owned hydropower dams are seeking FERC relicense in the next ten years. Relicensing is a chance for a reevaluation of the impacts of a hydropower dam's operations in a public waterway and is described by Chaffin and Gosnell as a "window of opportunity" to both negotiate for removal where endangered species are present and attend to federal commitments to tribal sovereignty where important cultural landmarks or resources are present [20]. However, relicensing brings with it a host of legal, logistical, and informational challenges that are not easily navigated by stakeholders without complete information. FERC data suggests that there are 135 dams expected to apply for relicensing between 2020 and 2029 in the Northeast alone, so it is an opportunistic time to strategize about participation by stakeholders and empower them to contribute to the relicensing process in a way that is impactful to FERC's decision process. My research focuses on the role of SHP dams in Maine's energy mix, as well as the stakeholders that are impacted by (or benefit from) powerplant operations at the dam, an internationally-relevant resource governance problem in the transition away from fossil fuels [5], [21]–[23]. I take a sustainability science approach in this research, which allows me to pragmatically address my research questions from multiple angles, crossing, spanning, and blending research disciplines as needed.

1.2. Hydropower Background

Most dams in the U.S. are non-powered. According to the U.S. Army Corps of Engineers (USACE) National Inventory of Dams (NID) database, only 7 percent of the total 91,457 U.S. dams generate hydroelectricity at present [24], so most dams were built for alternate uses (e.g., fire protection, flood control, drinking water storage). Many of these dams are old, especially in the Northeast region (with a mean age between 72 (Pennsylvania) and 119 years (Rhode Island) [25]), and may present safety risks [26], [27]. Hydropower industry, natural resource practitioners, academics, and stakeholders are all considering different futures for these dams. For instance, aging dams without hydropower (and even some powered dams) are prime targets for removal as a natural resource management or habitat restoration strategy [28], particularly if they are in rivers with historical sea-run fish migration [19], [29], [30]. Many NPDs are considered candidates for hydropower ([8], [9]) because existing infrastructure qualifies them as retrofit projects (there are virtually no 'greenfield' (i.e., new) hydropower developments in U.S. new stream reaches due to technical (few unexploited reaches with significant power potential) and social acceptance reasons [3]). SHP dams are important (particularly where they can take advantage of existing dam infrastructure) because they are a mature and long-lived renewable energy technology [1], providing load-following and grid support services that complement renewable electricity generation from other technologies (e.g., wind, solar) [1]. However, due to their smaller size, SHP projects appear to experience nonlinear economies of scale [14], meaning that for especially small (i.e., 'mini;, 'micro' or 'pico' (size definitions discussed in Ch. 2)) projects there is a fine line delineating what is economically feasible and what is not (Ch.3).

Despite a general understanding that size and project design plays a part in an SHP's economic feasibility, there is little agreement about definitions for SHP in the hydropower literature [21] (Ch. 2), even amongst U.S.-only studies (e.g., Kosnik [14] refers to 'small' as 1 – 30 MW, whereas an earlier study by Hall and Reeves [4] and a later study by Sandt and Doyle [31] refer to 'small' as 10 MW or less). Likewise, there is some disagreement about the environmental and social impacts of SHP. While many studies suggest that SHP is less environmentally impactful than larger hydropower projects (e.g., [3], [14]), Kelly-Richards et al. [21] emphasize that this is not necessarily true, that the design/scheme and governance matter when assessing social and environmental impact, and small projects should not be exempt from scrutiny. Results from other studies suggest that the location of the dam (e.g., mainstem vs. tributary [29]), as well as its age and physical size ([26]) matter in terms of environmental impact. Simply put, power capacity is an incomplete indicator of impact. Even low-capacity (below 1 MW) dams can still be environmentally or socially harmful.

Environmental impact and high up-front investment costs inspire careful consideration of SHP site viability. There are many published studies focused on the evaluation of SHP construction and operation using methods from top-down (i.e., regression-based; e.g., [11], [12], [32]–[41]) to bottom-up (i.e., engineering-economic; e.g., [9], [10], [13], [31], [42]–[55]) models for project cost assessment to more multi-criteria approaches (e.g., [18], [29], [56]–[61]).

Multi-criteria approaches are appropriate for sustainability science (section 1.3.) applications [61], so while I begin with a review of hydropower project cost and performance assessment models (Ch. 2) and then perform a cash flow-based assessment of small-to-medium-sized hydropower dams in Maine (Ch. 3), I then transition to consideration of more multi-criteria approaches (Ch. 4 – 5).

1.2.1. FERC Licensing

FERC licenses non-federally-owned hydropower dams in the U.S., many of which are privately held. As of 2006, 50 percent or more of all hydropower plants were privately owned in 33 of 50 states [4]. Cumulatively across the country, 69 percent of hydroelectric plants were privately owned, and the majority (85%) were characterized as small-to-medium-sized (1 – 30 MW) projects. Private utility owners held the largest percentage of SHP and micro-hydro assets in the U.S., followed by private non-utility owners [4], [62]. While the majority (829) of private hydropower owners each held only a single dam, there are a handful of private dam owners who each held 20 or more assets, with a single owner holding 77 hydropower assets (as of 2014) [4]. Ownership is still changing in states like Maine, where one or two private owners hold most hydropower assets, licensing them through subsidiary companies.

FERC issues operational licenses for a period of 30 – 50 years. The relicensing process begins five years before filing the license expiration date in what is referred to as a 'pre-filing' stage, where the licensee (temporarily referred to as 'applicant') seeks input from relevant parties (e.g., stakeholders) and identifies necessary studies to address the issues expressed by those parties [1], [63], [64]. The applicant must first choose a licensing process. There are three processes which FERC supports: Traditional Licensing Process (TLP), Integrated Licensing Process (ILP), and Alternative Licensing Process (ALP) [1], [65]. The ILP (which integrates the National Environmental Policy Assessment (NEPA) assessment and licensing, is considered FERC's default process) has collaborative and paper-driven aspects, pulling from both the ALP and the TLP; the ILP is the process which FERC typically recommends for licensees [63]. By contrast, the TLP limits FERC interaction until after the applicant files the official license application and is thus only recommended for experienced applicants with projects experiencing no change to their operations or impacting the surrounding environment and relevant stakeholders only minimally. The ALP is designed for maximum collaboration between relevant parties and may be preferred for non-commercial applicants, such as NGOs or municipalities with hydropower holdings, who want to emphasize transparency or ensure that stakeholder voices are being heard and needs are being met [65].

After identifying their preferred licensing process, the applicant must file an official Notice of Intent along with a Pre-Application five years in advance of the license application [1]. The Notice of Intent indicates that an official relicense application is forthcoming, while the Pre-Application highlights operations, project characteristics, and known environmental impacts [64]. The Notice is shared with relevant parties: agencies, tribes, municipalities, and interest groups, in addition to FERC [64]. After receiving the Pre-Application, FERC issues a scoping document describing the project's operational and environmental parameters, hosts a scoping meeting (with site visit), and requires the licensee to host a public hearing [63], [1]. Next, the applicant coordinates with FERC, other government agencies, and other key groups (such as tribal representatives or municipal officials) to develop a study plan proposal appropriate to the project relicense application (including the physical site as well as relevant historical or cultural, safety, environmental, and economic factors) [63]. Often the applicant hires consultants to perform the assessments and write up a plan for proposed mitigation and enhancement [64]. The study plan is submitted to FERC and parties identified in the Pre-Application [1], where FERC and others have an opportunity to issue comments before it is finalized in the actual license application.

Before license application submission, the applicant must renew their Water Quality Certification under the Clean Water Act (provisions must be stated explicitly in FERC license) [64]. Once the license application is submitted to FERC with all relevant study information and notification to all relevant parties, FERC develops the NEPA report and seeks input from relevant federal, state, and local agencies [64]. At this stage, FERC can accept the license application or ask for the applicant to address lingering issues [1]. Once the application is accepted, the post-filing environmental assessment is performed by FERC staff [63]. There is also a post-filing public comment period, at which time prospective interveners should apply with FERC for official intervener standing (personal communication, FERC employee).

Interested stakeholders may request to be on a FERC mailing list for the process to be notified of license status changes [63]. After the environmental assessment and public comment period, FERC gives the final license order (historically, few applications have been rejected outright by FERC [66]).

1.3. Sustainability Science and Stakeholder-Based Evidence

Sustainability science is pragmatic, problem-driven, and aimed at addressing the world's most pressing complex problems relating specifically to social-ecological interactions in coupled human and natural systems [67]–[69]. It is more often defined as an arena of research than a discipline [69], due to the multi-faceted approaches used to identify both sustainability problems and proposed solutions. Sustainability science research aims to produce "useable knowledge" for stakeholders that "links knowledge to action" [68], [70]. Kates et al. describe the integration of diverse perspectives in research as critical to 'doing' sustainability science [67]. Clark et al. urge researchers to (1) actively engage end-users in designing research pursuits from the outset, (2) integrate scientific process and innovative thinking with its application, and (3) recognize the advantages of bottom-up research shaped by local or institutional contexts in mind [70]. Whether stakeholders are government agencies (state or federal) whose mission identifies resource health, indigenous tribes whose cultural traditions and lifeways are deeply embedded in the resource, municipalities which define their borders by the rivers that flow alongside the shops downtown, or residents whose properties border the reservoir, stakeholder perspectives provide evidence toward the development of improved policy and resource management strategies [71], [72]. As such, stakeholder engagement has been embraced by sustainability scientists as a central requirement for research [69], [73], [74]; this being said, the quality of engagement matters.

Few, Brown, and Tompkins remind us that it is not enough to educate [75]; rather, if participation is the rhetoric used to invite or solicit stakeholder engagement in research, stakeholders expect genuine involvement. Reed et al. outline a set of guidelines for successful involvement of stakeholders in research and improved knowledge exchange to policymakers [76]: (1) capture and systematically represent diverse perspectives from a variety of stakeholders, (2) make a long-term commitment to shared learning, and (3) design research with tangible and intermediate impacts in mind. Researchers should also (4) cultivate reflexivity (i.e., acknowledging their positionality in the research and actively reflecting on whether the research activities are *working*). In high-quality sustainability research, end-users (from policymakers to citizens) are engaged in the "co-production" of knowledge [77]. Sustainability science is simultaneously collaborative, recursive, and generative, involving participants and incorporating stakeholder-based evidence early and often.

What can happen when stakeholder perspectives are not considered? In a retrospective U.K. study on community SHP, Bracken and colleagues investigate community perspectives about two micro-hydropower projects, residents' sense of inclusion in decision making, and perceived controversy over project outcomes [78]. Recreational users, residents, and local business owners had negative statements about how the project was operated; moreover, study participants expressed a feeling of being left out of the scoping process [78]. In a case study of clean energy and water supply conflicts in Mexico's Bobos-Nautla river basin, Silber-Coats describes the importance of community-centric narratives around SHP; residents excluded from scoping discussions reported that the management of the resource felt extractive and not at all beneficial to their communities [22]. In a study about collaboration in a U.S. FERC hydropower licensing, Ulibarri looks at the impacts of participation and evaluates the outcomes of collaboration on the hydropower regulated river system [65]. Ulibarri finds that active engagement enriched the licensing process for many participants, and suggests that while collaboration is not a panacea, creating multiple opportunities for stakeholder inputs results in enhanced decision-making outcomes [65]. Each of these studies calls for more stakeholder-inclusive approaches to decision making [78], [79], [22], [65]. It seems that meaningful participation by stakeholders can bring the policy or management decision a degree of trustworthiness. I seek to involve stakeholders in my research in a way that likewise builds trust and gets the issues "out on the table", so to speak, using methods and tools that address information gaps while supporting stakeholders' ability to participate in dam decision making. Stakeholder involvement in research is critical to sustainability science because it taps into multiple and diverse perspectives ([67]) and "links knowledge to action" ([68], [70]) to address problems that matter in ways that are salient to end-users.

1.4. Problem-Driven Decision Support

For researchers and practitioners working on a state, regional, or national planning scale, there is a push to develop tools for considering many dams at once [9], [10], [12], but site-specific features play an important role in the estimation of project costs [11], [12]. Assessment of dam impacts often focus on econometric measurement of social or environmental attributes (e.g., [80],[53],[54],[83]), but there are additional social values that are more difficult to monetize, including public acceptance, hydropower governance, and justice (intergenerational, process exclusion) [21], [22], [65], [79], [84], [85]. And, unfortunately, econometric and techno-economic modeling tools may not be easily understandable for a broad range of stakeholders. Ultimately, models should be understandable to the end-user or include sufficient instruction that the user may navigate the tool without the support of a researcher. Ideally, a decision support model would be open access, open-source, and include basic 'quick-start' information on how to tailor the model toward other applications. It is also important to note that not all models are well-suited for use in participatory contexts. I identify participatory Multi-Criteria Decision Analysis (MCDA) as a candidate framework for pragmatic, group participatory decision support because of the structure it provides to groups of decision makers considering different decision criteria and alternatives [71]. Decision criteria are the attributes or factors (e.g., annuitized project costs, greenhouse gas emissions, sea-run fish habitat area) that a decision maker must weigh when considering different decision alternatives, or project options.

MCDA typically has 5 steps: (1) defining decision criteria and alternatives, (2) harmonizing the criteria data, (3) normalizing the criteria data, (4) eliciting preferences (e.g., from researchers, stakeholders, decision makers), (5) aggregating normalized criteria data and preference values mathematically through weighting, and (6) ranking the aggregated scores to identify the final recommendation. Forms of MCDA may be considered transparent, especially if participants are involved in model development, and participatory decision support workshops may be designed to communicate the extent to which model application is appropriate. Participatory MCDA has a history of application in water resource contexts (see, for example: [59], [60], [86]–[93]), but the literature is still growing. I aim to contribute to the participatory MCDA literature on water resource management by developing a model that is both stakeholder-informed and stakeholder-tested. Creating useful decision support for stakeholders in FERC SHP relicensing is the end goal.

1.5. Dissertation Research

My research contributes to the larger academic conversation about the economic sustainability of SHP development and the growing literature about participatory MCDA in water resource management. I explore these research areas using a theoretical, evaluative approach to review the respective literatures and select appropriate models (for hydropower project cost estimation and participatory MCDA). I then use the models for application in (a) a benefit-cost analysis of small-to-medium-scale hydropower projects in Maine and (b) a case study of stakeholder-informed decision support tool development.

1.5.1. Small-Scale Hydropower (SHP) Literature Review

The first section of my dissertation focuses on SHP, assessing 35 peer-reviewed model and application studies, defining their approaches as ‘top-down’ (i.e., regression-based), or ‘bottom-up’ (i.e., engineering-economic). Despite an apparent global increase in SHP development, academics and practitioners still disagree about basic terminology (what *is* small hydropower?) and appropriate project costing approaches [21]. Building on the review of Kelly-Richards et al. [21] and earlier project cost estimation work from other researchers (see, for example [9], [10], [13], [31], [32], [34], [38], [39], [45], [51], [53], [94]), I review the literature on SHP, identifying trends in project cost and performance modeling and pointing out additional areas of confusion in the literature over project design and terminology. I clearly define different types of hydropower schemes (from pumped storage to run-of-river) and discuss differences in project performance assessment metrics (e.g., levelized cost of energy, benefit-cost ratio, internal rate of return, net present value). In my second chapter, I address the following research question:

What kind of model is best for SHP project cost estimation in the Northeastern U.S., with small, aging impoundments, given that "every dam is different"? (Ch. 2).

1.5.2. SHP Benefit-Cost Analysis

The shortage of hydropower project cost data hampers regional-scale planning for renewable investment and natural resource assessment, but it also impacts practitioners on a local scale. Dams that are licensed for hydropower operation through FERC impact public waterways, but citizens, community groups, NGOs, and even state and federal agencies generally do not have access to the kind of up-to-date project cost and performance information they need to participate impactfully in a FERC relicensing process. I perform a cash-flow assessment of 8 hydropower dam sites in Maine and use benefit-cost analysis to estimate annuitized project costs and greenhouse gas emissions avoided at each project. My results offer insights into the sensitivity of project costs to electricity pricing and discount rate, as well as the estimated net present value of different decision alternatives. I focus specifically on hydropower capacity expansion at existing powered dams, an avenue of analysis missing from many studies reviewed in Ch. 2 (see, for example: [9], [32], [37], [94]). My research supports the information-gathering efforts of dam decision makers, and my findings suggest not only the importance of economic conditions to the viability and success of SHP investment but the necessity of extending benefit-cost analysis in a multi-criteria approach to decision support. In my third chapter, I answer: *What can project cash flows tell us about the economic feasibility of potential decision alternatives for Maine's small-to-medium scale hydropower dams?*

1.5.3. Participatory Multi-Criteria Decision Analysis (MCDA) Literature Review

My review of group participatory decision modeling and MCDA assesses 25 peer-reviewed water resource management application studies. I find that the academic literature on group participatory MCDA emphasizes the technical aspects of decision-support tool development rather than the practical evaluation of the participatory process or assessment of the decision support tool user experience. Where participation is described, evaluation appears to be cursory, informal, or not part of the original research design. I categorize decision modeling approaches and participatory strategies using two dimensions (Model Complexity and Depth of Engagement), noting patterns in participatory decision-making approaches and models used. I assess the suitability of MCDA models for stakeholder participation and find that Weighted Sum (WS) MCDA, combined with a participatory approach called 'Scenario-Based Stakeholder Engagement' is the most appropriate combination for designing a Dam Decision Support Tool (DDST). I answer the following question: *What is an appropriate MCDA model for use in a group participatory, hydropower dam decision context?* (Ch. 4)

1.5.4. Case Study on Dam Decision Support Tool Development

In my case study application, I identify key needs from stakeholders interested in participating in FERC relicensing: reducing barriers to information access and enhancing capacity for participation. To support stakeholders in overcoming these key barriers, I co-developed a participatory DDST with a team of researchers. The DSST is tailored for the eight dams coming up for relicensing in the next 10 years on Maine's Penobscot River. It is an interactive space for users to consider diverse decision alternatives (e.g. keep and maintain or improve fish passage) and criteria to generate a ranked outcome for single dams or multiple dams. This outcome is a recommendation of first-best, second-best, etc. decision alternatives to support the user in their consideration of dam futures and to enhance the impact their participation may have in a relicensing process. I use case study methodology with three embedded studies (i.e., decision support workshops where a version of the tool was deployed with a group of participants) to describe and analyze the DDST development process. I use post-survey data and researcher observations to compare the user experience of each version of the model in (a) individual and group contexts, and (b) single and multi-dam decisions. Finally, I evaluate each version of the tool using the two dimensions (Model Complexity and Depth of Engagement) that I developed for my literature review (Ch. 4). I use interview methods and qualitative coding to identify criteria and alternatives for the DDST, as well as the site-specific project cost and greenhouse gas emissions avoided estimates that I developed in an earlier chapter (Ch. 3), annual electricity generation data, and estimates modified from Roy et al. [18] for a set of five environmental and technical criteria (e.g., reservoir storage, breach damage potential, properties impacted). I also use pre-survey data from participants for six social decision criteria (e.g., indigenous cultural traditions and lifeways, town/city identity, industrial historical importance, and aesthetics). I consider the evolution of the

DDST over time to answer the question: *How can a DDST be designed to overcome barriers of access and capacity better facilitate stakeholder participation in dam decision-making processes?* (Ch. 5).

1.6. Discussion

In FERC's hydropower relicensing, public participation is both a 'means' and an 'end', depending on the decision at hand [44]. What I mean by this is that a public hearing is a required process component, and FERC solicits public comments about specific hydropower dam sites (an 'end', fulfilling a legal requirement of the process). Public participation can also be a way to support or inform a decision (a 'means', e.g., for a municipality gathering input from its residents to make an informed decision to intervene legally in FERC relicensing). However, broad calls to public participation raise important questions over equity, the meaningfulness of participation, and the extent of engagement within the selected mode or method, as well as the practical challenges of stakeholder engagement (who, when, and level of influence participants have on the final decision) [44]. In the following chapters, I explore different stakeholder-identified needs for decision support and span disciplines as I use my annuitized project cost estimates in a WS model that underpins an MCDA-based decision support tool. The context is specific (Maine hydropower dams), so that the results (and the DDST) may be of use to stakeholders locally; however, the lessons apply to other dam decision-making contexts. Broadly, and despite the site-specific differences that drive decision making about FERC-licensed dams, my research supports the claim that there is space for natural resource planning at a multi-dam scale.

2.0. A COMPREHENSIVE REVIEW ON SMALL HYDROPOWER PROJECT COST AND PERFORMANCE MODELING[1]

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Abstract

Small-scale hydropower (SHP) is important to the U.S. energy mix as a non-intermittent renewable generation technology. The Department of Energy and its contracting National Laboratories seek additional new sites for development and assess existing non-powered dam infrastructure for additional generation capacity. The northeastern U.S. region has many SHP plants and thousands of non-powered dams, with many slated for removal. Decisions about dam futures are informed by the cost and performance of different project options, so an accurate estimation model is helpful to stakeholders seeking to weigh possibilities by costs and benefits. Unfortunately, the academic conversation about SHP is stunted by inconsistency in model descriptions and disagreement about the parameters used to define SHP (e.g., nameplate capacity or project design). We review the literature on SHP, identify a working definition of SHP, compare results from multiple studies, and compare across model types to identify a hydropower project costing approach appropriate for use with dams in the Northeast.

[1] This chapter is an in-progress journal manuscript that Dr. Sharon Klein and I have been working on together for the last three years and is in the final stages of revision prior to peer-reviewed journal submission. Some of the wording in this chapter is hers, but due to the iterative nature of our collaboration over the last three years, it is impossible to separate out which words are hers and which are mine. We are co-authors on this chapter, with the bulk of the writing, and all tables and figures completed by me.

Keywords: small hydropower, renewable energy, levelized cost of energy, capital costs, net present value

2.1. Introduction

River-based hydropower is a mature technology with a storied history in the United States. The U.S. river-based hydropower fleet has an installed capacity of 79.6 GW (as of 2015). When we consider the additional 21.4 GW capacity from pumped storage hydropower [1], hydropower generation represents half (50%) of U.S. energy from renewables [95]. Hydropower's importance lies in its reliability and flexibility in electricity generation, in addition to its status as a renewable resource (hydro generation is non-consumptive, as water is replenished through rain and runoff in the hydrological cycle). Hydropower provides grid-support services, too: load-following production, reserves, reactive power, voltage support, and restoration service [1]. Small-scale hydropower (SHP) provides distributed electricity generation and helps meet development and grid service expansion goals in rural areas [96]. SHP is a growing interest both in the United States and abroad as practical concerns about environmental impacts, energy security, and flexible generation take center stage in the conversation about sustainable energy [1], [14].

There is a robust international academic literature on SHP feasibility published within the last 20 years (see, for instance: [32], [34], [35], [44], [45], [47], [48], [53], [94], [97]). There is also a rich literature on SHP feasibility in the U.S. published by government agencies (e.g., U.S. Department of Energy (USDOE), U.S. Bureau of Reclamation (USBR), U.S. Army Corps of Engineers (USACE) and National Laboratories (e.g., Idaho National Laboratory (INL), National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory (ORNL)). The volume of hydropower resource and market assessment reports has grown in recent years in response to a push on the federal level to explore untapped hydropower resources and facilitate renewable energy growth through relaxed standards for certain project types (e.g., 2013 Hydropower Regulatory Efficiency Act[2]) or enhanced coordination across federal agencies to use

[2] The 2013 Hydropower Regulatory Efficiency Act (1) required FERC to shorten the licensing process for non-powered dam projects, (2) directed DOE to explore potential in existing infrastructures, (3) increased the exemption size (based on capacity) for non-powered dam projects from 5 MW to 10 MW, and (4) exempted conduit projects <5 MW.

existing infrastructure for hydropower generation (e.g., the 2005 Energy Policy Act[3]; 2010 memorandum of understanding between the USDOE, U.S. Department of the Interior (DOI), USACE[4]; 2016 USDOE *Hydropower Vision* report[5]). As such, hydropower capacity expansion at existing powered dams and new installation at non-powered dams (NPDs) are of interest to the USDOE [1].

The question of NPD development is especially relevant to the northeastern U.S. because the Northeast has a multitude (8,289 [24]) of small and aging non-powered or low-head impoundments. However, the region also leads the country in small dam removals [1], with 608 removed between 1912 and 2019 (39% of total U.S. removals) [98]. While some of these dam removals have been strategic, coordinated amongst key stakeholder groups at a watershed scale, and balanced in terms of hydropower generation and fish passage concerns [19], many have been more opportunistic, taking place as Federal Energy Regulatory Commission (FERC) licenses expire or as dams are surrendered [99]. Dam and hydropower decisions, whether planned or opportunistic, can be simultaneously efficient and equitable when made with full information about the decision alternatives (e.g., project options) available and their associated criteria (e.g., fish passage, civil works costs, electromechanical equipment costs, and other costs and benefits).

To provide more complete information about hydropower-related costs, we build on the work of Kelly-Richards et al. [21], who identify key areas of disagreement amongst academics and practitioners over the definition of SHP and critique predominantly capacity-driven (as opposed to design-driven) project cost calculation approaches. We also expand on the work of Mishra and Khatod [96], who succinctly review the academic literature to date on SHP cost modeling. In this review, we consider both project cost and power plant performance (annual electricity generation) models for SHP projects and identify their strengths and weaknesses. We compare regression-based (i.e., ‘top-down’) and engineering-economic

[3] The 2005 Energy Policy Act created tax incentives for renewable energy, including hydropower.
[4] The purpose of the 2010 memorandum of understanding was to optimize and increase overall hydropower generation across the U.S.
[5] The 2016 *Hydropower Vision* report serves as a signal to the hydropower industry, including power markets, dam owners/operators, turbine designers/manufacturers, and academics about resource potential and projected future opportunities for expansion.

assessment (i.e., ‘bottom-up’) models to determine which cost model(s) and/or approaches are appropriate for SHP development options in the Northeast, with its abundance of existing, low-head NPDs. Published reviews of the literature do not always distinguish between regression-based and bottom-up models; similarly, published studies are often cursory in their descriptions about the workings of hydropower plants and the reason for breaking costs out in certain ways. Thus, we break down the main components of different published models and compare reported estimates to put all models on a level, comparable, playing field.

We divide our literature review into four main sections: 1) defining SHP (section 2.2.1. – 2.2.2.); 2) defining and comparing performance assessment metrics (sections 2.2.4.); 3) reviewing cost models (sections 2.3.); and 4) discussion (section 2.4.). Within our review, we highlight two performance-cost modeling strategies. The first is regression-based, and we build on recent efforts by Filho et al. [35] to clarify top-down approaches, distinguishing between aggregated regressions (e.g., estimation of costs for a whole project at once) and disaggregated regressions (e.g., turbine-specific costs). The second is engineering-economic, where we provide some additional discussion of models (e.g., the U.S. Bureau of Reclamation (USBR) HydroAssessment2.0, Natural Resource Canada (NRC)’s RETScreen4, and Palisade’s @Risk), as appropriate. We identify and compare specific data sources, model limitations, and underlying assumptions to help us identify appropriate models for SHP cost estimation in the Northeast US. This work contributes to the growing academic literature on SHP cost estimation and performance assessment and will be important for dam owners and other stakeholders trying to decide the future of a dam.

2.2. What is SHP?

In general, the hydropower generation process works in the following way: water flows through a weir intake at the reservoir and is conveyed through the penstock to the powerhouse (typically referred to as ‘civil works’), spinning the turbine (considered ‘electromechanical equipment’, along with the generator). Mechanical energy from the spinning turbine is transformed into electric power through the generator, after which it is stepped up at the transformer and transmitted through transmission lines to be stepped down for consumer use in industrial, commercial, municipal, or residential settings [1], [100]. Hydropower uses the net head (distance from the surface of the reservoir water to the turbine minus losses from friction during conveyance) and flow of the water through the system (dependent on the flow of the river) to drive the turbine using a combination of pressure and moving water [100]. Turbines can be impulse-driven (using the kinetic energy of water sprayed through a nozzle at buckets on the turbine runner with no suction as the water exits the turbine housing), or reaction-driven, (using the combined pressure and movement of water through the turbine housing, where the runner is submerged in the flow) (Appendix A) [54], [100]. Hydropower projects are often classified based on their nameplate power capacity (e.g., MW). However, due to the wide variety of available SHP technologies, Kelly-Richards and colleagues recommend classifying SHP based on project design (e.g., physical and technical characteristics), rather than capacity. In this section, we review both types of SHP classification (Sections 2.2.1-2.2.2.) and discuss the main technology components that comprise an SHP project in general (Section 2.2.3).

2.2.1. Capacity-Based Classification

Hydropower capacity is often classified qualitatively as large, medium, small, mini, micro, or pico. However, exactly what capacity threshold constitutes “small”, is inconsistent on an international level [21], where values defining SHP range from <1 MW [19] to <50 MW [33] (Table 1). Similarly, there appears to be general disagreement over the sub-classes of SHP: small, mini, micro, and pico-hydro (Table 2). The greatest discrepancy about ranges appears over the “small” range, which extends from 200 kW (Table 2) to 50 MW (Table 1). There seems to be some general acceptance that “mini” hydropower projects are between 100 kW and 1,000 kW; “micro” projects are between 5 kW and 100 kW; “pico” projects are anything smaller than “micro” (<5 kW). We align our definition of “small” hydropower with the USDOE’s (10,000 kW or less) [1], which is consistent with the International Renewable Energy Agency (IRENA) definition [26]. For our purposes, SHP also includes mini, micro, and pico projects (i.e. we do not distinguish between these sub-classes for the remainder of the paper).

Table 1. Summary of international SHP capacity definitions.

Country/Region	Capacity Limit (MW)
Germany	1 [102]
Sweden	1.5 [103]
Italy	3 [102]
United Kingdom	5 [102]
France	8 [102]
Norway	10 [103]
United States of America	10 [33], [102], [103]
Australia	20 [33], [102]
Columbia	20 [33]
India	25 [33], [103]
Vietnam	25 [33]
Brazil	30 [33], [102], [103]
Canada	50 [102]
New Zealand	50 [102]
China	50 [102], [103]
Philippines	50 [102]
Indonesia	50 [33]
Table adapted from Mishra et al.[33], and IRENA [103]	

Table 2. Variation in SHP classification by capacity.

Class	Low (kW)	Medium (kW)	High (kW)
Small	200 to 25,000 [33]	<10,000 [1], [31], [10]	1000 to 30,000 [14], [104]
Mini	.1 to <1,000 [14], [104]	--	100 to <2000 [33]
Micro	<0.1[14], [104]	5 to <100 [33]	--
Pico	<5 [33]	--	--

2.2.2. Design-Based Classification

SHP project designs are diverse: traditional reservoir-based impoundment, run-of-river (ROR), pumped storage (PS), and hydrokinetic (Table 3). The following subsections describe each of the designs in more detail. For consistency, we focus on dams that are privately owned or otherwise licensed through FERC. Note that while PS and hydrokinetic are discussed here as hydropower designs, they are less common in the Northeast region, so models that explicitly estimate PS or hydrokinetic project costs are not considered in the remainder of the paper.

Table 3. Comparison of SHP Designs

Design	Type	Design	Operation	Regulation	Application
Reservoir-based dams	Impoundment	Civil works block the flow of water downstream to control release through turbines. Turbine types can vary widely [100], [105].	Baseload, intermediate (load-following), or peaking. Low-head impoundments can be operated as run-of-river (e.g. Archimedes Screw turbine [100]).	FERC-regulated; may qualify for exempt license (10 MW or less) – a one-time application and approval process [1], [106], [107].	Most common type of hydropower (also called ‘conventional’).
ROR	Diversion	Weir channels water from the stream for generation and returns to the stream through tailrace [21], [100]. Turbine types can vary widely.	Operated roughly as outflow=inflow[1]. Seasonal river flow determines if baseload, intermediate, or peaking possible – may be intermittent	Same as reservoir-based dams.	Ranges from a single development to cascading developments as a part of a single project [21], [108].
PS dams	Diversion or off-stream	Draws water from a lower reservoir and pumps uphill to holding tank, releasing water back to the lower reservoir through turbines to meet peak demand [109].	Functions as a battery, storing potential energy in a reservoir until needed; typically peaking [1]; can be coupled with solar to power active pumping time [110], [105].	Same as reservoir-based dams; may qualify for a license exemption if not on a navigable waterway[106], [107].	Vary widely (in-ground, aquifer, ‘Energy Islands’); may exist entirely off-stream, limiting aquatic wildlife impacts [1], [109].
In-stream turbines	No diversion or impoundment	Reaction turbines designed to go directly into the flow of water; vary from kinetic/free-flow turbines to bulb-style turbines.	Intermittent: generation is entirely dependent on streamflow.	Same as reservoir-based dams.; canal or conduit projects qualify for a license exemption if <40 MW [106].	Range from canal/conduit to substrate-mounted, or even floating; may be applied in marine contexts as well (tidal or ocean current power)[100].

2.2.2.1. Reservoir-Based Dams

Traditional impoundment hydropower is also referred to as a dam-toe design and can be thought of as a dam across a river. This type of SHP can be installed on existing NPDs as a retrofit (also called upfit) project or newly constructed at new stream development (NSD, also called ‘greenfield’) sites; in both cases, a reservoir is created behind the dam, interrupting the flow of the river and storing water in the impoundment [21], [102]. *Design:* A reservoir-based project generates hydropower through predictable and controllable water releases from the reservoir through a gate and down the penstock to the turbine(s) (Figure 1). Reservoir-based dams projects completely block off the flow of water downstream except through turbines, via spillway, or even over the top of the dam in the case of lower head structures. The impoundment structure can be concrete, earth, rock fill, or wood (although this last type is mostly being removed or replaced) [1]. *Operation*: Reservoir-based dam operations are flexible; they can operate as baseload generation facilities (meeting the baseload grid demand), intermediate generation facilities (which come online as demand rises above baseload), or as ‘peaking’ facilities (where large quantities of water are temporarily released to meet high energy demand, drawing down the reservoir in the process) [1]. *Regulation:* In navigable waterways and U.S. lands, non-federally owned dams fall under the regulatory jurisdiction of FERC [1]. *Application:* Most hydropower systems are reservoir-based, so they are popularly referred to as ‘conventional hydropower’.

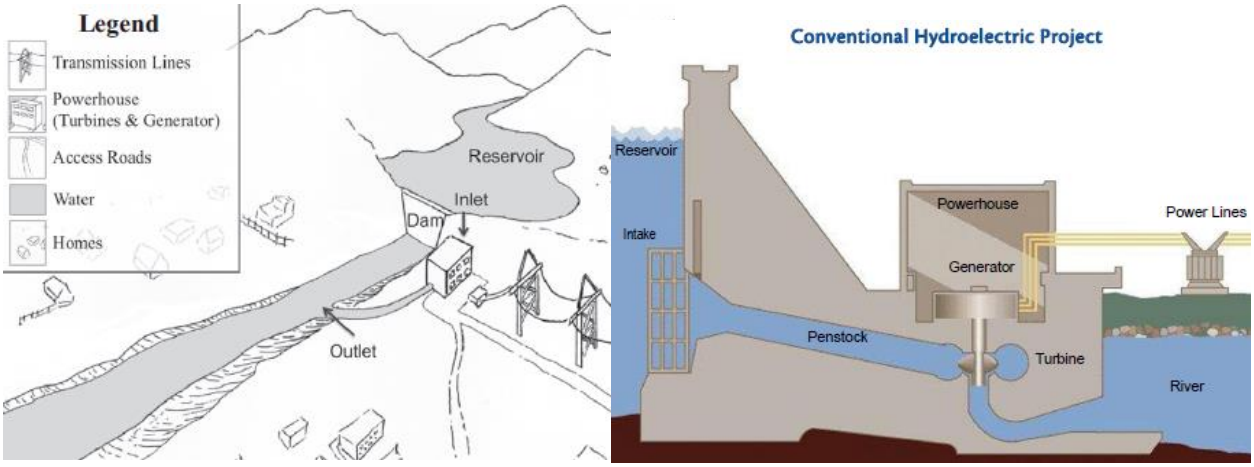

Figure 1. Reservoir-based hydropower design and schematic. Source: adapted from Kelly-Richards et al. *[21]* and FERC *[63]*.

2.2.2.2. Run-of-River (ROR)

Design: ROR systems typically use a diversion (a small, dug side stream or pipe) to channel water away from the river and into a settling tank where rocks, leaves, sediment, and other suspended solids drop out of the water column. The water flows from the settling tank, past the gate (usually with some kind of screen to catch remaining solids), and down the penstock to the powerhouse [21], [78], [108]. Water is returned to the river through the tailrace (dug trench or manufactured pipe used to channel water from the powerplant back to the river). ROR hydropower does not fully interrupt the flow of the river; instead, these projects divert part of the river's flow away from the main part of the river or allow some water to spill over a dam so that the discharge of water downstream of the diversion (outflow) is equal to the flow upstream [1]. However, in practice, cascading run-of-river hydropower designs can dewater a river as much as any impoundment (Figure 2) [21]. Kelly-Richards and colleagues [21] offer a thorough discussion of the differences between high and low head ROR diversion designs.

Operation: Because ROR projects divert rather than impound the flow of streams or rivers, they are typically operated as baseload generating plants when outflow equals inflow [1]. However, because they are required to have outflow equal to inflow, they can be more susceptible to seasonal or other changes in river flow and therefore, may not be as reliable as reservoir-based dams for year-round baseload power production. *Regulation:* ROR dams are subject to the same FERC regulatory process as reservoir-based dams and therefore, may face the same regulatory hurdles unless the project's nameplate capacity is <1 MW [106]. Generally, if the project is diverting only some of the flow, there is less habitat disruption and impact on fish passage than reservoir-based dams [1], [85], [111], so mitigation requirements may not be as steep as for reservoir-based projects. *Application:* ROR dams are gaining international popularity because of the potential lowered environmental impacts they offer in comparison with reservoir-based hydropower dams, but Kelly-Richards et al. warn that ROR systems can be just as environmentally harmful (e.g. disruption of habitat and reduced in-stream water availability) as conventional hydropower systems when multiple developments are used in a single, cascaded project (Figure 2) [21]. Also, ROR projects that use a full impoundment and rely on spillover to balance inflow and outflow can cause just as much environmental damage as conventional systems when seasonal precipitation and water flows are too low to enable spillover.

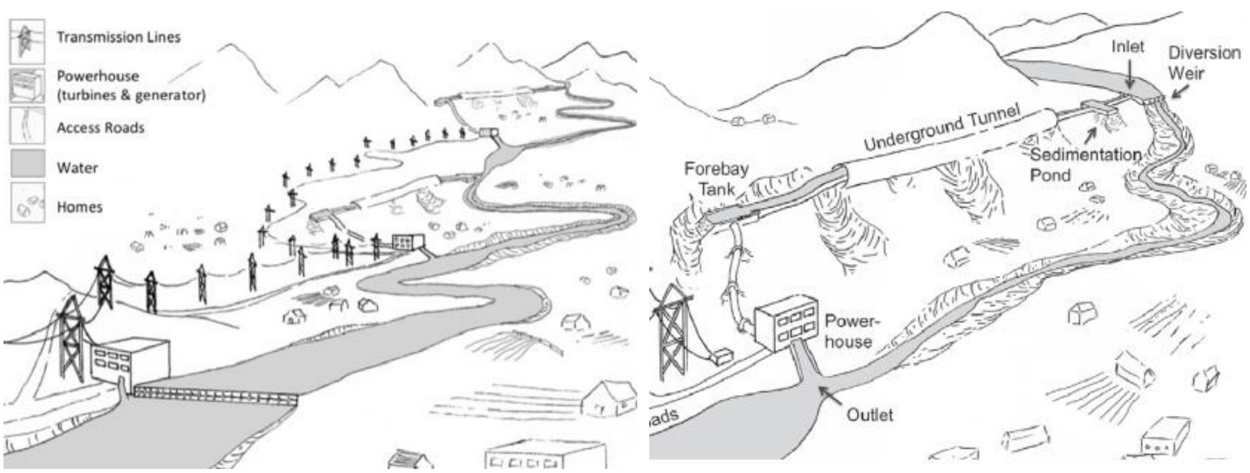

Figure 2. Run-of-river hydropower designs. Left: a project with cascading developments, right: a project with singular development. Source: Kelly-Richards et al. *[21]*.

2.2.2.3. Pumped Storage (PS)

Design: Basic PS designs use two reservoirs (Figure 3) and can draw from a river or stream or can be completely off-stream (called closed-loop PS). Newer PS designs emphasize the use of existing hydroelectric power plants or other energy infrastructure (civil works and electromechanical equipment from conventional hydro, or old mine shafts for below ground designs)[1]. PS projects also typically use reversible pump/turbine units [109]. *Operation*: PS projects actively pump water ‘uphill’ to a holding tank or reservoir during periods of low or off-peak electricity demand (when baseload generation is sufficient) and release water during periods of peak demand, essentially acting as a battery by storing energy for later use [1], [6], [85], [112]. The U.S. electricity storage capacity is nearly all PS [1]. *Regulation:* Most PS plants were built 30 years ago [109], but the regulatory environment is improving for PS as state-of-the-art designs emerge (i.e., fewer restrictions and accelerated license application review for closed-loop PS) [1], [106]. *Application:* The USDOE 2016 *Hydropower Vision* report and ORNL’s *Multi-Year Research Plan* each has a thorough discussion of PS applications [1], [6] ranging from in-ground designs (e.g. off-stream projects often recycling below-ground natural gas or petroleum holding tanks) to ‘Energy Islands’, fabricated islands with an interior lake below sea level from which water is actively pumped (using electricity generated by floating solar PV panels or near-shore wind-turbines) out to sea and passively channeled back in to generate electricity [1], [85].

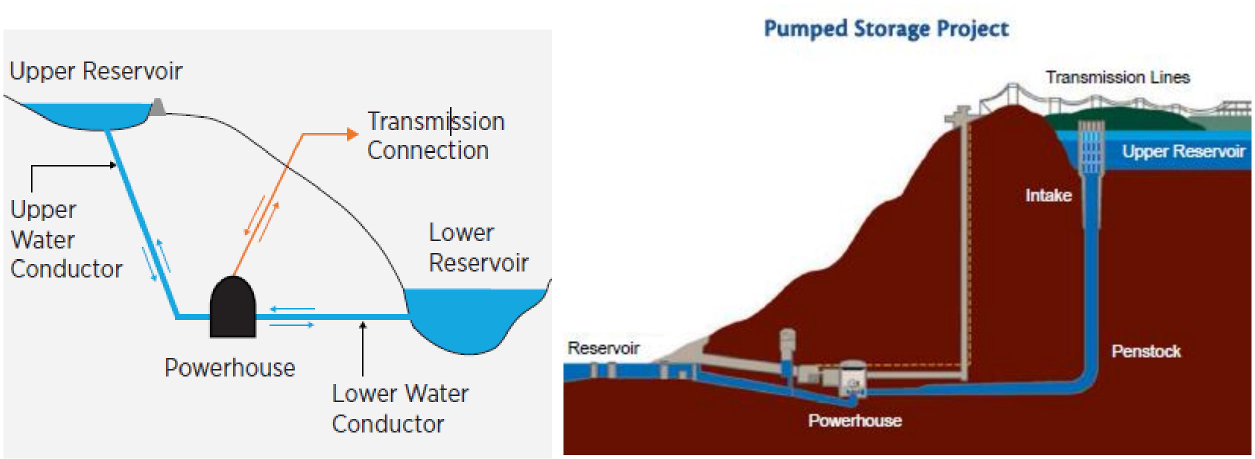

Figure 3. Pumped storage hydropower project design. Source: adapted from USDOE [1] and FERC *[63]*.

2.2.2.4. Hydrokinetic

Design: In-stream hydrokinetic turbines are designed to work directly in the flow of water, without a dam, and generate electricity from the in-stream flow of water [100]. These in-stream turbines can be situated at the base of the dam (e.g., at the end of the tailrace) on the downstream side, taking advantage of conventional hydropower releases [108]), substrate-mounted, or mounted on floating buoys [63].

Operation: In-stream turbines rely on the kinetics of the flowing water for operation [100]; thus, they are more susceptible to variation in river flows than conventional hydropower and may produce intermittent electricity. *Regulation:* FERC considers expedited licenses with shorter terms and requirements for proof of application preparation for small hydrokinetic projects than for conventional SHP [63]. *Application:* The USDOE and FERC both consider this type of hydropower system as a fairly new application of hydropower generation technology, so there are few applications from which to generalize [1], [63].

2.2.3. SHP Technology Components

The major components included in SHP designs are civil works, electromechanical equipment, and transmission equipment (Figure 4). Civil works include the structures that impound, divert, convey, or hold water, as well as the structure (powerhouse) that houses the electromechanical equipment (i.e. equipment involved in generating electricity). The transmission equipment (transformer, transmission lines) is typically considered separately from the electromechanical equipment and often considered apart from the SHP project itself in most top-down or regression-based costing models that are chiefly focused on estimating cost based on capacity. The pressure from the hydraulic head and flow (movement of water in the stream) (Figure 5) turn the turbine, which moves the shaft attached to the generator [100]. While there is generally some head loss from friction as the water is conveyed through the penstock and turbine casing, engineers account for this in the design of the civil works structures.

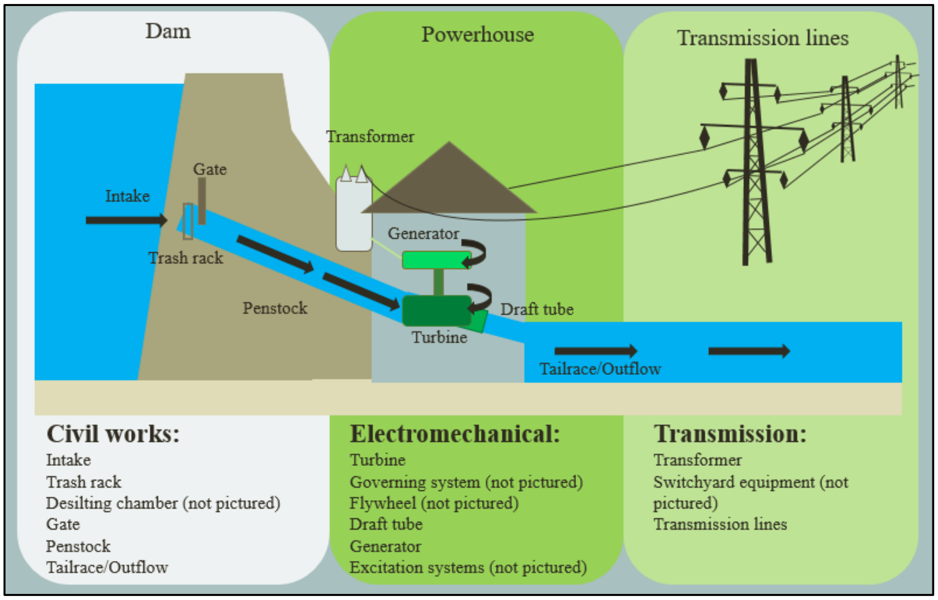

Figure 4. Typical hydropower project components. Source: adapted from IRENA *[103]*.

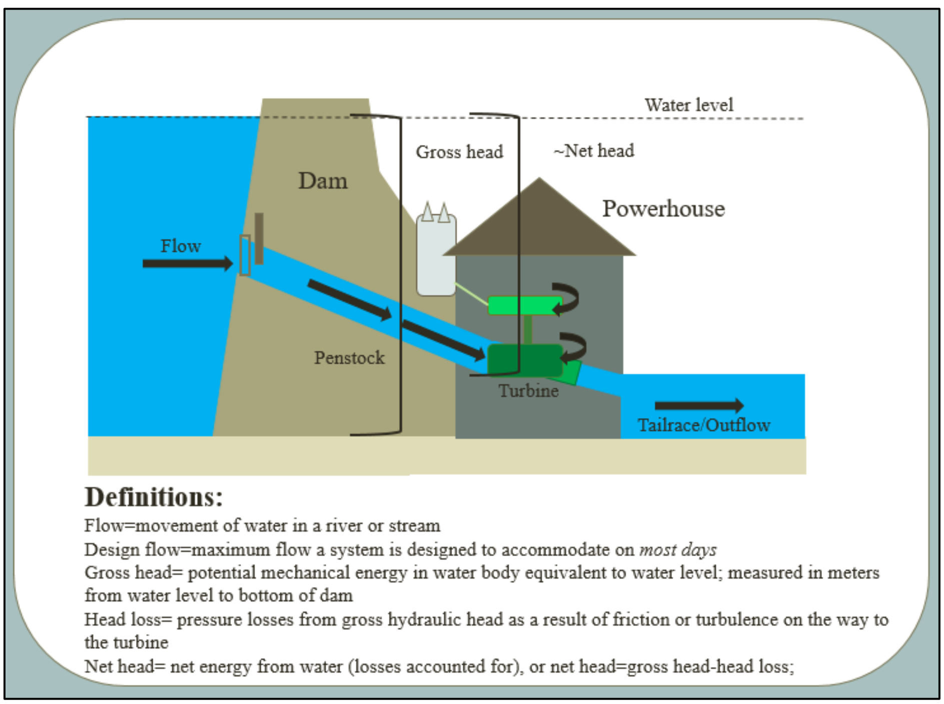

Figure 5. A powered dam's hydraulic components. Source: adapted from IRENA *[103]*.

Because of the site-specific nature of hydropower project assessment, there has been a recent push from the USDOE [1], National Laboratories [6], and hydropower interest groups [113] for more modular design of civil structures, modular and flexible water conveyance equipment, and standard turbine/generator assemblies. The push for modular design somewhat resembles the trend toward component manufacturing in other industries; Oak Ridge National Laboratory and others are recommending pre-set modules to guide research and development efforts (e.g. generation module, passage module, interconnection module, see *Multi-Year Plan for Research, Development, and Prototype Testing of Standard Modular Hydropower*) [6].

As far as actual progress made by the hydropower industry, there are state-of-the-art linear turbine/generator technologies (where the generator and turbine are in line with the stream to reduce head loss) being developed for extremely low heads [114], which potentially eliminate the need for a penstock, and can embed the generator in the turbine runner (e.g. as a cap or 'nose') [6]. Even civil works are being modified; some companies are developing inflatable dams or weirs [115], while others are re-envisioning hydropower as river-restoration compatible. There is also research that seeks to optimize generation using multiple turbine types, efficient under different head/flow combinations, to maximize generation year-round [116]. Finally, there is considerable research and development for variable speed turbine units, which seek to optimize generation within changing flows using a single turbine unit [1], [6], [109]. Appendix A summarizes existing turbine technologies. For our review of SHP cost studies (section 2.3.), we focus on reservoir-based and ROR SHP projects because they are the most common in the Northeastern U.S.

2.2.4. SHP Performance Assessment (Electricity Generation)

The main factors determining theoretical hydropower potential (Eq. 1 [7], [96], [105], [117]) at a reservoir-based site are head, flow, and turbine system efficiency [7]. Head, or vertical drop (measured as distance), is a function of altitude change. Gross head (Eq. 2 [108]) is calculated based on head race (inflow) and tailrace (outflow) levels. Net head (Eq. 3-4 [116]) accounts for site-specific friction losses during water transport [108]. Flow (Eq. 5 [108]) is the speed of water through the stream or river channel (measured as volume per unit time) and is a function of the geomorphology of the riverbed and precipitation – specifically, the width, depth, and slope of the riverbed. In practice, any flow above the design flow (Q_{30}) is 'spilled' by a spillway or other outlet (e.g. through turbines) [7]. The turbine system efficiency is based on the technology and appropriate match to site conditions [105], [108], and is a function of the arrangement of turbines installed to optimize generation over a range of flows [105], [117]. System efficiency is the electrical power output ($\rho g Q_{30} H_n$) divided by the hydraulic power input (*P*), achieved by rearranging Eq. 1 to solve for η [118]. Typically, this value is estimated by the turbine manufacturer (e.g., 85% [9]). Annual electricity generation is calculated as hydropower potential times annual turbine operation time (hours). SHP project owners/operators optimize electricity generation in a variety of ways, including: setting restrictions on discharge for ROR operations and replacing/removing small/inefficient turbines to increase flows (discharges) for other larger/more efficient turbines in the same system [94].

$$P = \eta \rho g Q_{30} H_n \tag{1}$$

where P = power (W), η = turbine system efficiency (%), ρ = water density water (kg/m^3), g = acceleration due to gravity (m/s^2), Q_{30} = 30% "design" flow rate (m^3/s) [3], [4], *H_n = net head (m),*

$$H_g = \frac{HRL - TRL}{1.25} \tag{2}$$

where Hg = gross head, HRL = head race level, TRL = tail race level, constant accounts for friction,

$$H_n = H_g - (\delta h_1 + \delta h_2 + \delta h_3) \tag{3}$$

$$\delta h_i = \left(\lambda_i * \frac{L_i}{D_i} + \zeta_i\right) * \frac{8P_t^2}{\pi^2 g D_i^4} \tag{4}$$

where δh_i = head loss for a section of penstock (i=1, 2, 3), λ = linear loss coefficient, L = length, D = diameter of penstock, P_t = nominal power of the turbine, ζ = minor loss coefficient,

$$Q = [(B * d) + (S * d)d] * V \tag{5}$$

where Q = volumetric flow rate, B = width of riverbed, d = depth of flow, S = slope, V = water velocity.

2.3. A Review of Hydropower Cost Estimation Approaches and Models

SHP project cost studies typically employ at least one of two main modeling approaches: "top-down" regression-based models (also known as "parametric"), or "bottom-up" engineering-economic models (also known as techno-economic assessment). Most top-down SHP models estimate capital expenditure (C_{CAP}): the sum of direct construction costs (land/water rights, civil works, electromechanical equipment, transmission lines) and indirect costs (licensing, permitting, engineering, management, administration, inspection, and environmental provisions), by running regressions on data from multiple hydropower sites. Top-down models are based on real data but may be prone to error when used across larger ranges of head or flow. Hydropower literature often uses C_{CAP} interchangeably with initial capital costs (ICC); however, the term ICC refers more specifically to the investment cost and is used as a rough measure of feasibility based on a project's installed capacity (section 2.3.4.). By contrast, C_{CAP} is typically reflective of contingency costs as well as ICC and is considered a complete picture of upfront cost. Bottom-up models simulate the performance and cost of a specific hydropower plant at a specific real or hypothetical site, calculating C_{CAP} and indirect costs by adding up component costs specific to the site. One or more of 4 different measures are typically used in the assessment of project cost-effectiveness: net present value (NPV), internal rate of return (IRR), benefit-cost ratio (BCR), and levelized cost of energy (LCOE). These metrics are helpful because they combine C_{CAP} and other relevant measurements to help investors assess project cash flows and performance.

In this section, we review a total of 36 peer-reviewed papers: 19 application-only studies, 5 model-only studies, and 11 hybrid studies (model & application) each of which uses different types of modeling (regression-based, engineering-economic, or mixed) to estimate a variety of hydropower cost metrics (Table 4). All dollar values reported in this section have been converted and escalated to USD 2019 using the Consumer Price Index[6]. A total of 16 studies report NPV estimates, but only 9 studies report BCR values (even though BCR aids in the interpretation of NPV), and only 10 studies report IRR (though the rate of return likewise aids in the interpretation of NPV). C_{CAP} is the metric most used to discuss project feasibility (32 studies). The number of sites considered in each study ranges from 1 – 125,000, but this maximum value is one of only two studies reviewed that consider >1,000 sites and are thus outliers; 25 studies consider less than 100 sites. While 80 percent of studies report the turbine type considered, only 46 percent report turbine designs other than the conventional Pelton, Francis, or Kaplan types.

[6] For all urban consumers (CPI-U) 1913 – 2019, where the base year (CPI = 100) is 1982. See https://www.usinflationcalculator.com/inflation/consumer-price-index-and-annual-percent-changes-from-1913-to-2008/ for the full 2013 – 2019 CPI-U dataset.

Table 4. Overview of related SHP articles.

Author(s)	Year	Study Type	Model Type	Model Name	Location	No. Sites	Project Type	Turb. Types	Power (kW)	NPV	IRR	BCR	LCOE	C_{CAP}
Hall et al. [119]	2003	A, M	R_{dis}	NS	USA	2,155	NPD, NSD, Dams w/ power	K, Fr, B	1,000 – 1,300,000	N	N	N	N	Y
Kaldellis et al. [55]	2005	A, M	EE	NS	Greece	1	NSD	K	50 - 10,000	Y	Y	N	N	Y
Park [54]	2006	A	EE	RET-Screen	California, USA	285	NSD, NPD, Ca/Co	K, Fr, Pe, Cr, Tur, Pr	100 - 1478	N	N	N	Y°	Y
Bockman et al.[37]	2007	A, M	R_{agg}	NS	Norway	3	NSD	Pe	4,500	Y	N	N	N	Y
Anagnostopoulos & Papantonis [116]	2007	A, M	R_{dis}	NS	Greece	1	Dams w/ power	Pe, Fr	860 - 8,720	Y	Y	Y	N	N*
Forouzbakhsh et al. [53]	2007	A	EE	NS	Iran	2	NSD	Fr	1,750 - 60,000	Y	N	Y	N	Y
Singal & Saini [40]	2008a	M	R_{dis}	NS	India	70	Ca/Co	Tb	2000 - 10000	N	N	N	N	Y
Singal & Saini [120]	2008b	M	R_{dis}	NS	India	NS	NPD	Pr, K, FR, Tb, B, Cr	0 - 25000	N	N	N	N	Y
Pletka & Finn [121]	2009	A	EE	NS	USA, Canada (British Columbia, Alberta)	NS	NSD, NPD, Dam w/ power	NS	0 - 1000000	Y°	N	N	Y°	Y
Aggidis et al. [41]	2010	A	R_{dis}	NS	UK	82	NSD	K, Fr, Pe	25-990	N	N	N	N	Y

Table 5. (continued)

Author(s)	Year	Study Type	Model Type	Model Name	Location	No. Sites	Project Type	Turb. Types	Power (kW)	NPV	IRR	BCR	LCOE	C_{CAP}
Singal et al. [122]	2010	A	R_{dis}	NS	India	24	NSD	Tb	1,000 - 24,750	N	N	N	N	Y
Kosnik [14]	2010	A	EE/R_{dis}	RET-Screen, Norwegian-Macro	USA	125,000	NSD	NS	10 - 30,000	N	N	N	N	Y
Santolin et al. [32]	2011	A	R_{dis}	NS	Italy	3	NSD	K, Fr, Pe	NS	Y	Y	N	N	Y
USBR [10]	2011	A	EE	Hydro-Assessment2.0	Western USA	530	NPD	K, Fr, Pe	6 - 25,800	N*	Y	Y	N	Y
Alonso-Tristan et al. [52]	2011	A	EE	RETScreen4	Spain	1	Dam w/ power	K	400	Y°	Y	Y°	Y	N
Zhang et al. [102]	2012	A, M	R_{agg}	NS	Oregon, USA	73	NPD, NSD, Ca/Co	K, Fr, Pe, Ax, Cr, Tur	NS	N	N	N	Y	Y
Mishra et al. [33]	2012	M	R_{dis}	NS	Multiple	22	NSD	K, Fr, Pe	NS	N	N	Y°	Y°	Y
IRENA [103]	2012	A	NS	NS	International	NS	NSD, NPD, Ca/Co, PS, Dams w/ power	K, Fr, Pe, Cr, Tur	NS	N	N	N	Y	Y
Sandt & Doyle [31]	2013	A	EE	RETScreen4	North Carolina, USA	49	NPD	Cr	1 - 168	Y	N	N	N	Y
Zhang et al. [13]	2013	A, M	EE	ORNL-HEEA	Oregon, USA	29	NPD, Ca/Co	K, Fr, Pe, Cr, Tur	1 - 4,650	N*	Y	Y	Y	Y
USACE [9]	2013	A	EE/R_{agg}	NS	USA	223	NPD	K, Fr, B	1,000 - 130,000	N*	Y	Y	Y	Y

Table 6. (continued)

Author(s)	Year	Study Type	Model Type	Model Name	Location	No. Sites	Project Type	Turb. Types	Power (kW)	NPV	IRR	BCR	LCOE	C_{CAP}
Motwani et al. [51]	2013	A	EE	NS	India	1	NSD	Pu	3	N	N	N	Y°	Y
Kusakana [50]	2014	A	EE	HOMER	South Africa	2	NSD	Hk	4 - 6	Y°	N	N	Y°	Y
Cunha & Ferreira [49]	2014	A, M	EE	@Risk	Portugal	1	NSD	K	1900	Y	Y	N	N	Y
Adhikary et al. [48]	2014	A, M	EE	RET-Screen	India	1	NSD	NS	6000	Y	Y	Y°	Y	Y
Gagliano et al. [47]	2014	A, M	EE	Mado-Watt	Italy	1	Dam w/ power	Pe, Fr	77	Y°	Y	Y°	N	Y
O'Connor et al. [123]	2015	M	R_{agg}	BCM Version 2	USA	680	NPD, NSD, Ca/Co, PS, Dams w/ power	NS	11 - 2,250,000	N	N	N	Y	Y
Carrapellucci et al. [45]	2015	A	EE	NS	Italy	87	Dams w/ power	K, Fr, Pe, Cr, Tur	500 - 10,000	Y	N	N	N	Y
Nair & Nithiyananthan[44]	2016	A	EE	RET-Screen	Malaysia	1	NSD	Pe, Fr, K, Tu	467 - 506	Y°	N	N	N	N
Zema et al. [94]	2016	A, M	EE/R_{agg}	NS	Italy	3	NPD, Ca/Co	Pe, Cr	101 - 313	Y	N	N	N	Y
Cavazzini et al. [34]	2016	A, M	R_{dis}	ASD-PSO	Spain, Italy, Guatemala	49	NSD	K, Fr, Pe	25 - 2,753	N	N	N	N	Y
Balkhair & Rahman [43]	2017	A	EE	NS	Pakistan	20	NSD, Ca/Co	K, Tur	179 - 561	N	N	N	Y°	Y
Akcay et al. [42]	2017	A	EE	@Risk	Turkey	1	NSD	NS	7500 - 30000	Y°	N	N	N	Y
Filho et al. [35]	2017	A	R_{dis}	Solver	Brazil	21	NSD	Fr, Pe, K	1000 - 21300	N	N	N	N	Y

Abbreviations: A = application, M = model, EE = engineering-economic, R = regression-based (subscripts indicate aggregated or disaggregated cost estimation), NSD = new stream development, NPD = non-powered dam, PS = pumped storage, Ca/Co= canal/conduit, Pr = propeller, Pe = Pelton, Pu = pump as turbine, Hk=hydrokinetic turbine, K = Kaplan, Fr = Francis, B = Bulb, Tur = Turbinator, Tb = tubular, Cr = crossflow, Ax = axial flow; * = used but no value or calculation actually stated, ° = we do not discuss these studies in detail here in Chapter 2 but will for journal submission.

2.3.1. NPV Application Studies

NPV is the sum of the present value of benefits (positive) less costs (negative), where the present value is calculated by dividing by (1+discount rate (*r*)) raised to year *t* (Eq. 6). NPV is the end-result of a discounted cash flow analysis, representing the cumulative annual project revenues (losses) in today's value. The primary benefits in SHP are energy production times energy price, and the costs generally include C_{CAP} to construct the power plant and annual O&M costs. The discount rate is an indication of the opportunity cost or risk associated with the project. When comparing two projects with identical upfront costs and expected future benefits (typical of renewable power generation), if we apply a high discount rate to one project (A) and a low discount rate to the other project (B), project A will likely have a lower NPV than project B. A project with NPV equal to zero means that a rational decision-maker should be indifferent to the project investment because cumulative benefits and costs are equal. A positive NPV is a general indicator of a project's overall viability, whereas the numeric value of the NPV indicates the quality of the investment: higher NPV implies a better investment. IRR, another indicator of project performance, is complimentary to NPV because it suggests the profitability of the investment: the higher the IRR in relation to the discount rate, the more profitable the investment. IRR indicates the discount rate at which the NPV is equal to zero (set the NPV equal to zero and solve for the discount rate, *d*, to calculate IRR).

$$NPV = -C_o + \sum_{i=1}^{T} \frac{b_i - c_i}{(1+d)^T} \tag{6}$$

where C_o *= initial investment cost; T = total project lifetime;* b_i *= annual benefits for year i;* c_i *= annual costs for year i; d = discount rate.*

We review 7 studies that assess NPV, only one of which is in the United States (Sandt and Doyle [31]) and none of which are in the Northeastern U.S. (Table 5) . Nearly all of these studies are bottom-up, with two (Bockman et al. [37] and Zema et al. [35]) being a hybrid that includes a mix of bottom-up and top-down approaches. The full dataset can be found in Appendix B.

Table 5. Comparison of net present value mean estimates

Author(s)	Location	No. SHP Sites	Project Capacity (kW)	Discount Rate	Electricity Price (USD 2019 /kWh)	Project Lifetime (years)	NPV (millions USD 2019)	NPV (USD 2019/ kW)	Electricity (MWh/yr)
Kaldellis et al. [55]	Greece	1	*10,000*	10%	$0.10	20	NS	NS	*38,400*
Anagnostopoulos & Papantonis [38]	Greece	1	*5382*	10%	NS	20	$8.7	$1,231	20012
Forouzbakhsh et al. [53]	Iran	1*	_3107*_	6-20%	NS	50	$7.9*	$2,629*	9989*
Bockman et al. [37]	Norway	3	*4500*	5.80%	$0.04	30	$3.6	NS	9,330
Santolin et al. [32]	Italy	3	NS	5%	$0.35	15	$8.9	NS	40000
Sandt & Doyle [31]	North Carolina	49	85	5%	$0.14	30	$0.5	$6,723	355
Zema et al. [94]	Italy	3	174	NS	$0.11	25	$1.6	$9,400	875
Adhikary et al. [48]	India	*1*	*6000*	*NS*	*$0.07*	*35*	*$5.7*	*$953*	*NS*

Italicized values represent single estimates provided, not an average; NS=Not Specified; * = Forouzbakhsh et al. [53] estimate NPV for a range of power capacities and a range of discount rates, so the average capacity is reported here.

Kaldellis et al. [55] use an extended version of Eq. 6 in an engineering-economic model for assessing SHP plant feasibility, including additional factors such as taxes and water fees (specific to Greece). There were 20 years of hourly flow data available for the Tsimovo NSD study site, where expected annual electricity generation ranges from 20,000 MWh to 70,000 MWh. The authors calculate IRR from 10 – 21.12%. Unfortunately, the corresponding NPV estimates are only graphed, labeled as decimal values (between -0.8 and 1) without units, which leaves us confused about the actual results and unable to compare them meaningfully with the results from the other studies reviewed.

The engineering-economic model used by Anagnostopoulos and Papantonis [116] is based on site-specific flow-duration curves as input to Eq. 1 for building a new SHP plant and an NSD site. The numerical algorithm simulates a year of operation for a power plant with a cumulative nominal power production across 2 turbines of at least 50 kW and no more than 10 MW. The authors use optimization software developed by the Laboratory of Thermal Turbomachinery that uses evolutionary algorithms to select turbine type and size (measured by power capacity) ratio to optimize five objectives (energy production, load coefficient, streamflow fraction passing through 1 – 2 turbines, NPV, and BCR) one at a time (with NPVs ranging from $-1.7 to $13.4 million) and two at a time (with a possibility frontier of results), with site-specific input parameters. Anagnostopoulos and Papantonis report that maximum NPV is achieved with two Francis turbines at a size ratio of 0.5, a total power capacity of 5 MW, and a total nominal flow rate of 3 m^3/s. The authors also perform a sensitivity analysis on their model to examine how the annual discount rate, construction cost, electricity price, and hydraulic conditions affect NPV results. Anagnostopoulos and Papantonis provide a detailed explanation of their power plant simulation algorithm; however, they include few details of their economic calculations, reporting only the main economic components used (2 years construction period, subsidization, taxation, electricity price escalation, interest rate, and financing), but providing no numeric values or citations for data or studies informing these values [116]. They do not include an equation for calculating annual revenue or NPV.

Forouzbakhsh et al. [53] compare the BCR and NPV of multiple power rating alternatives for one small (1.8-5 MW) ROR and one medium (5-60 MW) reservoir-based hydropower plant at two different sites in Iran. Their primary goal is to examine the effect of the percentage of private sector investment (e.g., 100%, 75%, 25%, 0%) in a “build operate transfer” (BOT) investment arrangement on NPV and BCR. Although the authors present a detailed discussion of the main components of the analysis (site-specific flow-duration curves; capital, indirect, and O&M costs) and explain and cite data sources for these components, they do not include any equations or explanation of the actual calculation of energy, NPV, or BCR. They report NPV results for 14 different power capacity-defined alternatives for the SHP plant ranging from $-2.28 million (0% private ownership, 20% discount rate, and converted/escalated) to $19.3 million (100% ownership, 6% discount rate)) and 25 capacity alternatives for the medium-size plant. We do not discuss the medium-sized plant results here because they exceed our definition of SHP (<10 MW). Forouzbakhsh et al. also report NPV for 8 different interest (discount) rates (6-20%). The optimal project, with an installed capacity of 3.75 MW and an NPV of $7.2 million is for 100% private ownership, with an interest rate of 10%. The analysis by Forouzbakhsh et al. results in greater NPV and BCR values for increasing percentages of private investment at all discount rates; however, the authors do not report equations they used (this would help the reader understand precisely how the private investment offsets costs). Forouzbakhsh et al. also calculate the debt coverage ratio, return on equity, and LCOE for the two types of hydropower plants (section 2.3.3.).

Bockman et al. [37] examine the economic feasibility of developing SHP projects with Pelton turbines at three technically feasible project sites. Although they calculate NPV, Bockman et al. neither report a detailed cashflow analysis nor sum the annual present value of the net annual benefit (or cost) for annual cash flows (as in Eq. 6). Rather, they calculate the second term in Equation 6 by multiplying annuitized net marginal benefit ($/MWh) by energy production (MWh) and sum the result of that calculation (Eq. 7) with a calculation of an investment cost that reportedly includes fixed O&M costs (Eq. 8), but the authors are not transparent about the source of the dataset they use to obtain the regression constants for Eq. 8. Their NPV calculation is not the primary objective of the paper; rather, Bockman et al. focus on a real options analysis with continuous scaling to calculate the minimum electricity selling price (P) “trigger” needed to achieve a positive NPV, indicating profitability. They calculate average energy production (which they dub "capacity" – a term usually applied to power capacity) by setting NPV to zero and solving Eq. 7 for *m*. They estimate power capacity using simulation, referring to a cash flow spreadsheet they mention at different points throughout the article but never thoroughly explain; the underlying simulation likely includes a version of Eq. 1, relying on site-specific flow-duration curves based on historical flow data. They only reveal the power capacity for one of their three case study sites, and since they do not specify the "simulation" used to convert from energy to power, we include the single reported power capacity value in Table 4, rather than an average as we did for the other Bockman et al. parameters in Table 4.

$$NPV = -C_o + m(P_r - c)(1/\delta)\left(1 - e^{-\delta T}\right) \tag{7}$$

where C_o = initial investment cost; m=average annual energy production; P_r = shadow price of electricity ($/MWh); c = variable O&M cost ($/MWh), which is equal to the sum of delivery, grid, and sales costs; δ =growth-adjusted cost of capital (%) equal to the discount rate minus expected electricity price growth rate; T= project lifetime (years).

$$C_o = Ae^{bm} \tag{8}$$

where A and b are constants determined through regression on an array of data (of unspecified source) briefly discussed by the authors.

Based on an existing long-term electricity price of $0.06/kWh (escalated from 2007 EUR to 2019 USD), Bockman et al. conclude that two of their three case study projects (14 GWh/yr and 8 GWh/yr) should be initiated right away because the price trigger ($0.04/kWh) for both projects is less than the long-term price. Project 3 (5 GWh/yr) demonstrates the potential value of the real options approach because the NPV is positive, which usually signifies a good investment, but the trigger price is above the current electricity price signifying an undesirable investment. NPV results range from $1.5 to $8.8 million, but unfortunately, we do not know the nameplate capacities of Projects 2 and 3, so we cannot compare the NPV/kW values for all sites and are limited in our ability to compare with results from other studies.

Santolin et al. [32] develop a model using site-specific flow-duration curves and Eq. 1 to optimize project power capacity at 3 SHP projects. Like Kaldellis et al. [55], Santolin et al., focus on single-turbine SHP in Italy, with NPV (calculation similar to Eq. 6) and IRR the main financial indicators of a project's success. Like Anagnostopoulos and Papantonis [116], Santolin et al. produce an array of results for different turbine types (Francis, Pelton, and Kaplan) and power capacities. The authors generate 3-dimensional surface estimates for turbine type, energy production, turbine dimension, installation height, machine cost, NPV, and IRR across three specific sites, with NPV ranging from $-0.6 to $28 million. Due to the 3-dimensional nature of their reported estimates and the lack of additional information in the article text, we are limited in our ability to compare this (Santolin et al. [32]) with other studies.

Sandt and Doyle [31] build on earlier work (e.g., [37], [116]) in their exploration of the cost-effectiveness of 'upfitting' 49 low-head (15 ft to 35 ft) NPDs with small hydro (<2MW) in North Carolina. The authors use RETScreen4[7] (a proprietary renewable energy cash flow analysis software program from NRC) to calculate NPV and assess the sites for development potential, assuming annual revenues based on electricity sales, benefits from greenhouse gas emission reductions, and annual costs limited to O&M and financing payments (numeric values not reported). They also use RETScreen4 to perform a Monte Carlo analysis on the 49 NPDs to "determine site-specific relationships between design parameters and the key financial indicator (i.e. NPV)" [31]; however, the authors do not disclose the actual equation used to calculate NPV. They adapt RETScreen4's standard flow duration curves to be more site-specific by using existing USGS stream gages in the study region, to estimate site-specific energy production. We classify Sandt and Doyle's approach as bottom-up because of its classic cash-flow approach to NPV estimation and site-specific approach to estimating energy production. Sandt and Doyle [31] suggest that larger (0.3-2MW) SHP projects are more generally economically valuable than micro-scale SHP projects (<.3MW). They justify their statement using an estimated "Financial Viability Trendline": a 2-dimensional plane with hydraulic head on the y-axis and impoundment drainage area on the x-axis, extending from high head (32

[7] RETScreen4 is the name of the software program, acronym not identified in the software documentation (http://www.nrcan.gc.ca/energy/software-tools/7465).

ft) and low drainage area (30 mi^2) to low head (15 ft) and high drainage area (110 mi^2), with two NPV zones (>0, viable; <0, non-viable). Fifteen projects with drainage areas > 65km^2 achieved a positive NPV for electricity prices between $0.08/kWh and $0.20/kWh [31]. Overall, NPV results ranged from $-0.5 million to $1.6 million [31]. The authors conclude that projects less than 50kW are not economically feasible in the study region.

Adhikary et al. [48] examine SHP NPV for a single 6000 kW site using RETScreen4 bottom-up estimation software. Like other studies using RETScreen4n, no equations are indicated for the NPV calculation; however, Adhikary et al. do share a cumulative NPV graph and, unlike Alonso-Tristan et al. [52]. They also provide screenshots of each of the RETScreen4 results tables (cost analysis, financial analysis, GHG analysis, and cumulative NPV). The NPV estimate for the site is $5.7 million. The authors inaccurately compare RETScreen4 with forms of Multi-Criteria Decision Analysis (MCDA), a structured decision support framework that allows the decision maker to compare multiple types of decision criteria (attributes or factors to consider; e.g., project costs, annual electricity generation, greenhouse gas emissions reductions) across multiple decision alternatives (project options; e.g., improve hydropower generation, keep and maintain dam as-is). MCDA typically normalizes decision criteria data for ease of comparison, and then uses decision maker preference information or some other weighting scheme to weigh the normalize data and calculate a score for each decision alternative. Scores are then ranked from best to worst. The outcome is a recommendation for the decision maker, a ‘first best’ decision alternative, based on their preferences or weights. To be sure, RETScreen4 is a multi-criteria renewable energy decision support tool, but it hardly constitutes an MCDA (see Ch. 4 for a complete review on MCDA).

Zema et al. create a model to site turbines and select optimal turbine power capacity for micro hydropower (<1MW) projects in an existing irrigation scheme (i.e., canal/conduit sites) and apply their model to compare three installation schemes (with 4-7 turbines each) in an existing irrigation network (3 small NPDs, 3 surge tanks) in Calabria, Italy. Their model calculates power production using Eq. 1, return on investment (ROI), and NPV (no equation provided, but the description suggests a version of Eq. 6). They identify 5MW as the smallest turbine power capacity to be economically feasible (annual profit >6%

ROI) and find maximum NPV results ranging from $1.1-$2.6 million across the three schemes. The authors note that annual operating time plays a large part in micro (<300kW) SHP NPV (in a wet year, NPV can be up to 55% higher than NPV in a dry year). They also find that a low number of high capacity plants is equivalent in terms of profits to a high number of lower capacity plants; however, it is worth noting that the non-monetary tradeoffs between those hydropower generation schemes may be considerable [5]. Zema et al. do not try to calculate non-market values for the noted tradeoffs for the micro-scale SHP projects in their study.

The lowest NPV estimate is $-2,043/kW [116] while the highest estimate is $11,502/kW [94] (Figure 6). This variation can likely be explained by different geographic locations, site characteristics, and internal assumptions used in each study (e.g., discount rate, electricity price). For instance, Forouzbakhsh et al. explored discount rates up to 20%, but concluded that 10% was more realistic for interpretation of results [53]. Average electricity prices range $0.04-$0.35/kWh across studies as well. We have no mean value for Santolin et al. [32] or Kaldellis et al. [55], so we did not plot these studies on the graph. In general, there seems to be a negative relationship between NPV and capacity, but there are too few studies (and sites), with too many different inputs, to draw any meaningful conclusions about patterns.

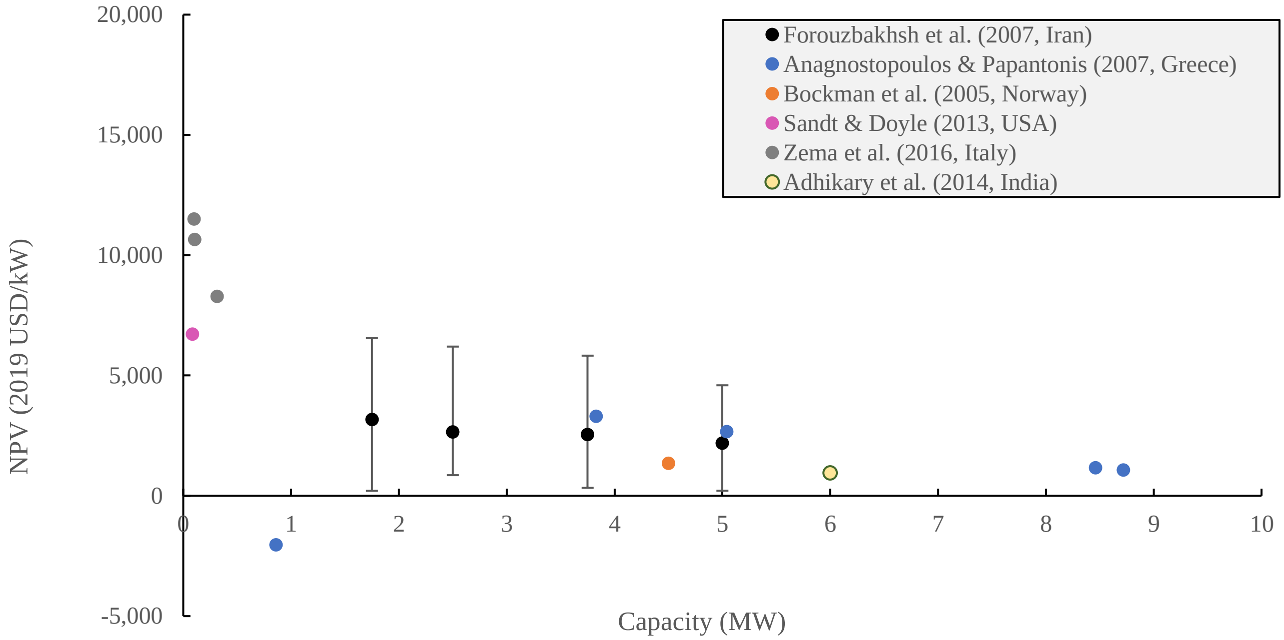

Figure 6. NPV trends across application studies reviewed. Bars around Forouzbakhsh et al. [53] data points indicate the range of NPV outcomes for each simulated site (defined by power capacity), where the point is the mean NPV specific to the power capacity.

2.3.2. BCR Application Studies

BCR is the ratio of the strict NPV of benefits to the strict NPV of costs (Eq. 9, [13]), offering a slightly different measure of cost-effectiveness than standard NPV (Table 6, full dataset Appendix C). Whereas a positive sign signals cost-effectiveness for NPV, a value greater than 1 signals cost-effectiveness for BCR. If the BCR=1, then the project NPV=0, and the project will break even over a given lifetime, which is still viable, but potentially not worthwhile to some investors. Five studies we review use BCR to evaluate the development potential of NSD sites [13], [53], [116]. The studies were performed primarily in the United States, where government-sponsored reports use discount rates between 4 and 6 percent (e.g., [9], [10], [13]). The two international studies, Anagnostopoulos and Papantonis [38] (Greece) and Forouzbakhsh et al. [53] (Iran) use much higher discount rates, 10 and 13 percent, respectively. The average BCR values across most studies exceed 1.0, except for Zhang et al. [13]. Average reported BCR is a strange way to summarize the literature, so we recommend that the reader explore Appendix C, which contains site-specific BCR information.

$$BCR = \frac{\sum_{n=1}^{N} \frac{Benefits}{(1+d)^{N}}}{\sum_{n=1}^{N} \frac{Costs}{(1+d)^{N}}} \tag{9}$$

where N = project lifetime (years); d = discount rate (%)

Table 6. Comparison of BCR mean values.

Author(s)	Location	No. SHP Sites	Capacity (kW)	Annual Generation (MWh)	Discount Rate (%)	BCR
Anagnostopoulos & Papantonis [116]	Greece	1	*5040*	*20012*	*10*	*1.7*
Forouzbakhsh et al. [53]	Iran	1*	*3750*	*11570*	*10*	*2.7*
USBR [10]	Multiple States, USA	32	2830	14247	4	1.4
USACE [9]	Multiple States, USA	12	5001	17262	4	1.4
Zhang et al. [13]	Oregon, USA	29	933	3903	6	0.7

Italicized values represent single estimates provided, not an average; ***** = Forouzbakhsh et al. estimate BCR using multiple project capacities and discount rates (single optimized outcome reported here).

Anagnostopoulos and Papantonis [38] restrict their study to a single site and vary estimates across a range of capacity factors (but not discount rates; see Section 2.3.3. for a definition of capacity factor). The authors presumably calculate BCR using Equation 9, but no equation is stated in the paper. Reported BCR estimates range from 0.82 to 2.3. While the authors conclude that their projects with higher capacities fare better in terms of BCR (>1) than projects with lower capacities [116], they are hesitant to describe BCR as an indication of cost-effectiveness (i.e., that there is a correlation between SHP project capacity and BCR). While they acknowledge that BCR and plant size (i.e., power capacity) are related, Anagnostopoulos and Papantonis instead recommend developing a BCR curve (resembling a production possibility frontier, or concave curve) with NPV on the x-axis and load coefficient (i.e., capacity factor) on the y-axis, where the 45-degree angle would describe the cost-effective load coefficient/NPV pairing. In this case, the cost-effective capacity range is 4.6 – 5.5 MW (optimal capacity: 5 MW, with an estimated BCR of 2.3).

As with their estimation of NPV, Forouzbakhsh et al. [53] estimate BCR in terms of the ratio of private to public powerplant ownership. The authors also explore the impact of changing discount rates (0% -20 %) on BCR values. While BCR values are typically higher for 100 percent privately-owned plants, a few of the simulated plant alternatives do cross the BCR = 1 threshold for 0 percent private ownership. Under public ownership (0 % private), the BCR ranges from 2.15 (6% discount rate) to 0.44 (20% discount rate), while under private ownership (100% private), the BCR ranges from 5.11 (6% discount rate) to 1.04 (20% discount rate). BCR (like NPV) has a negative relationship with the discount rate, where BCR decreases in proportion to increases in discount rate [53]. The BCR corresponding to the optimal NPV value of $7.2 million is 2.67 (10% discount rate, 3.75 MW power capacity).

The USBR study [10] examined 530 existing and USBR-owned NPD and canal/conduit sites in the Western United States (i.e., Great Plains, Lower Colorado, Upper Colorado, Mid-Pacific, and Pacific Northwest regions) using their Hydropower Assessment Tool's (referred to as HydroAssessment2.0), a bottom-up Excel-based and freely accessible model.[8] USBR collected data from the USBR-owned dams under consideration for the study. The user inputs head and flow data for the site, and the tool calculates electricity generation (average monthly and annual estimates), electromechanical equipment, and civil works costs, as well as economic benefits. The tool identifies a Pelton, Kaplan, Francis (see Appendix A for turbine comparison), or modified Francis turbine for the powerplant based on the flow data [124], so costs and electricity generation estimates are tied to turbine type. Electricity generation is based on the turbine, its efficiency, and the flow input. The HydroAssessment2.0 tool estimates transmission costs as well if the user knows the distance to the nearest transmission/distribution line. The benefits (i.e., revenues from electricity sales and forecasted prices (using a forecasting model called AURORAxmp, with no additional description provided) are calculated with and without the addition of 'green incentives', i.e. financial benefits like tax credits or grant programs and then further escalated based on state price trends. We include only the BCR estimates without green incentives in our comparison (Table 6) to be consistent with other studies. BCR is calculated using a 50-year project lifetime and a 4.4 percent discount rate. Estimated BCR values range from 0 – 2 (similar to Forouzbakhsh et al. [53]). The authors do not state their calculation method, but we assume that they use Equation 9 (prescribed for federal resource assessment

[8] USBR's HydroAssessment2.0 Tool is publicly available for download at: http://www.usbr.gov/power/AssessmentReport/USBRHydroAssessmentToolVersion2.0.xlsm.

studies). The authors identify 191 of the total 530 study sites as technically feasible, but far fewer as economically feasible (the BCR>0.75, which they use as the threshold in this preliminary/site scoping threshold is set at BCR>0.75, for this study, in a departure from the expected BCR > 1.0). While the authors report 70 sites with BCR> 0.75, only 46 sites that have a BCR > 1 (all located in the western U.S.). Seventy sites with BCR > 0.75 is inclusive of sites >10 MW and 'green incentives' in the calculation of BCR [9]. Limiting our comparison to sites 10 MW or less and BCR without green incentives lowers the total number of sites with BCR >1 to 32. For these sites, BCR ranges from 1.01 – 2.86. Because this is a preliminary study over more than 100 sites, the authors do not offer their estimates for an 'optimal' BCR like Anagnostoupolos and Papantonis [38] or Forouzbakhsh et al. [53].

Zhang et al. [13] estimate BCR and LCOE for 29 SHP sites (14 NPDs, 15 canal/conduits) in Oregon, USA using ORNL [125], USGS, Pacific Northwest National Laboratory (PNNL) [126], USBR [10], and Oregon Water Resources Department historic daily flow data for each site. Zhang et al. developed a tool (Hydropower Energy and Economic Assessment, HEEA) that builds on previous cost estimation work (see [102]) and is designed to be used independently or integrated into the Basin-Scale Water Management Model, now called Water Evaluation and Planning system (WEAP) developed by PNNL [127]. The HEEA model is bottom-up, Excel macro-based, and flexible: it supports the user in assessing energy potential and economic feasibility, handling several turbine technologies in addition to the standard Pelton, Kaplan, and Francis types (e.g. Propeller, Cross-flow, Turgo, hydroEngine, and Turbinator, though the user must specify efficiencies and capacity factors for the latter three technologies). The authors compare it to NRC's RETScreen4 and USBR's HydroAssessment2.0 tool in terms of the site-specificity and engineering features (e.g., turbine selection) offered. The authors claim an advantage over RETScreen4 and HydroAssessment2.0 in dealing with indirect costs and project finances (i.e., incentives), but ORNL-HEEA was never publicly released (personal communication, 2017). Zhang et al. report that the HEEA model is most suitable for projects from 0.01 MW- 50 MW. In their assessment of SHP development potential in the Deschutes River Basin, Zhang et al. use a discount rate of 6 percent (lifetime not stated) and a threshold of BCR=1 for project feasibility [13]. BCR is calculated using Equation 9, and like the USBR study [10], Zhang et al. [13] calculate BCR both with and without ‘green incentives’. For consistency, we exclude BCRs calculated using ‘green incentives’ and limit our comparison to sites with a power capacity of 10 MW or less. Of this smaller set, there are only 6 sites with BCR > 1; however, the authors consider projects under 2,500 kW to be non-viable, leaving only 4 NPDs and 4 canals/conduits considered to be feasible for development. Because the feasibility assessment includes ‘green incentives’, the number of economically feasible sites drops to 3 when excluding those incentives from the BCR calculation. Where the USBR study [10] was generous with the BCR considerations (i.e., BCR > 0.75), Zhang et al. [13] are more critical. They use the BCR calculation as an opportunity to narrow the total number of feasible sites.

The USACE study uses projections from the Energy Information Administration’s *Annual Energy Outlook* 2013 estimates for annual end-use energy generation costs and calculates benefit values using the Northwest Power and Conservation Council’s projected monthly electricity prices over 50 years [124]. As with the USBR study [10], the dam sites in the USACE study [9] are owned and regulated by USACE, so the data are internal to the organization. Like USBR, USACE does not offer the actual BCR equation, but because they are a federal agency, we can again assume that they use Equation 9. Some (146) of the USACE-owned NPDs in the assessment are considered economically feasible (informed by metrics such as IRR and BCR) for hydroelectric development, though 74 of those (75 percent of the economically feasible projects) already had pending or preliminary FERC permits at the time of publication [9]. We limit our sample of data from this extensive report to the powerplants ≤10 MW in the top 20 values reported for BCR, leaving a total of 12 SHP sites, with BCR ranging from 1.10 to 2.42. USACE does not differentiate between BCR with or BCR without green incentives, so we assume the values are estimated without.

We plot USACE data for power plants ≤10 MW, along with Zhang et al. [13], Anagnostopoulos and Papantonis [38], Forouzbakhsh et al. [53], and USBR [10] (Figure 7) for a more effective visual comparison. The lowest BCR is 0.09 [13], while the highest BCR value is 5.11 [53]. Many of the very small power plants (e.g., < 1MW) have BCRs lower than 1.00, whereas the larger power plants (e.g., >6MW) have BCRs greater than 1.00. Two of the power plant capacities tested by Anagnostopoulos and Papantonis [38] and most of the sites for Zhang et al. [13] are below the 1.00 ‘viability’ threshold.

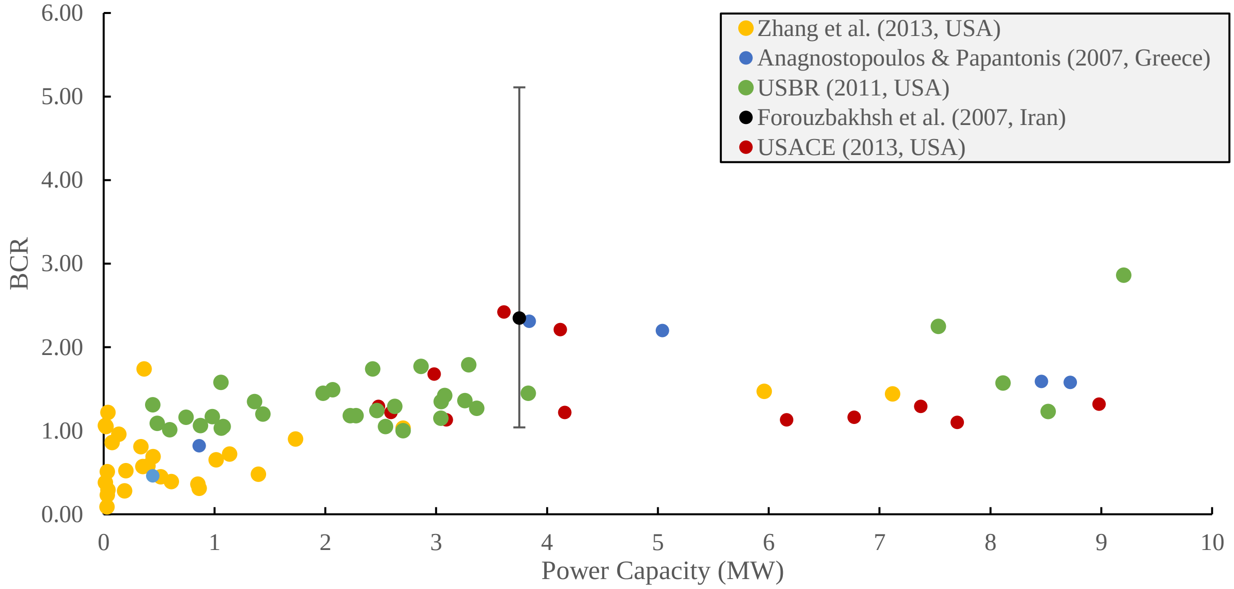

Figure 7. Project BCR estimates by nameplate capacity. Note: Forouzbakhsh et al.'s BCR estimates are represented here as an average, with bars added to give a sense of the range of estimates reported (they varied discount rate at the site for which BCR is reported).

2.3.3. Levelized Cost of Energy (LCOE)

LCOE (Eq. 13-15 [102]) is a calculation of average cost per unit electricity production: the ratio of the sum of annuitized C_{CAP} and annual O&M costs to annual electricity generation. LCOE is often used as a relatively quick (compared to cash flow analysis) way to compare hydropower to multiple electricity generation technologies and prevailing electricity prices [11]. While high BCR (>1) and NPV (>0) values are considered better than low BCR (<1) and NPV (<0) values, lower LCOE values are better than high ones because it is indicative of cost. LCOE equal to the price of electricity indicates the project is breaking even; LCOE>electricity price indicates loss; and LCOE<electricity price indicates positive returns [103]. LCOE does not indicate whether a project is economically or technically viable in the same way NPV, IRR, and BCR do because it does not typically include discounted cash flow analysis and therefore does not typically explicitly address the value of seasonal (e.g., intermittent flows) or operational (e.g., peaking vs baseload or ecological protection decisions) changes in electricity production [21]. However, much like NPV, IRR, and BCR, LCOE can also act as an indicator of operational efficiency and thus has a role in long-term capital planning [46] (a concept that is not explored in this paper).

The annual capacity factor (Equation 10) is important to understanding power plant performance with LCOE. Capacity factor is the ratio of the average annual energy production (*AEP*, measured in megawatt-hours per year and typically an observed data value) to the maximum *potential* level of electricity generation (the denominator of Equation 10: based on the nameplate power capacity, *P*, and estimated as if the power plant were operating at peak capacity 24 hours a day, every day of the year, with no variation in operations due to changes in flows or maintenance shutdowns). Capacity factor reflects the reality that the power plant may only reach that potential level of electricity generation only half of the year (e.g., capacity factor = 50%). One variable or the other would be observed LCOE (Equation 11, [13]) can be calculated once we know the average annual energy production and some information about costs (discounted, annuitized C_{CAP} and annual O&M costs, estimated either using regression or as a percentage of C_{CAP}).

$$Capacity\ Factor = \frac{AEP}{P * 24_{hrs} * 365_{days}} \tag{10}$$

where P= power capacity (MW), AEP is observed,

$$LCOE = \frac{L(\mathrm{C_{CAP}}) + O\&M}{AEP} \tag{11}$$

where L= fixed charge rate, used to annuitize costs ($/yr); O&M = O&M cost ($/yr),

$$\mathrm{L} = r + \frac{d}{(1+d)^{T} - 1} + tax \tag{12}$$

T = project lifetime; d = discount rate (%); tax = tax rate (%, optional).

Note that *AEP* indicates that the LCOE levelizes annuitized costs over *actual* electricity generation, not *potential* generation. *Fixed charge rate (L)* factors in the time cost of money (i.e., discount rate, considered to be the project return [13]), as well as the tax rate. Ten studies estimate LCOE for SHP, with values ranging from $0.04 to $0.19/kWh (Table 7), with an average value of $0.11/kWh. Project lifetime ranges from 18 – 50 years and the discount rate ranges from 4 -12 percent, as we have seen with BCR and NPV.

Table 7. LCOE estimate comparison.

Author(s)	Location	Capacity (kW)	Capacity Factor (%)	Discount Rate (%)	Project Lifetime (years)	LCOE Estimate (2019 USD/kWh)
IRENA [103]	Multiple, International	NS	49	*7*	*NS*	*0.096*
Zhang et al. [12]	Oregon, U.S.	5300	45	NS	NS	0.087
Zhang et al. [13]	Oregon, U.S.	933	1	6	NS	0.189
Alonso-Tristan et al. [52]	Spain	400	0	4	50	0.080
Gagliano et al.	Italy	NS	NS	8	20	0.162
Adhikary et al. [48]	India	6000	NS	NS	35	0.046
O'Connor et al. [11]	U.S.	17750	NS	6	NS	0.133
Carapellucci et al. [45]	Italy	NS	NS	5	30	0.167

Italicized values represent single estimates provided, not an average. NS=Not Specified

The International Renewable Energy Agency (IRENA) study [103] reports a range of LCOE for refurbishments and upgrades to existing small dams (no power capacity specified) around the world (no specific locations or data mentioned). The LCOE is calculated using Equation 11. The IRENA LCOE estimates correspond to capacity factor values between 20 percent and 95 percent, and range from \$0.03/kWh to \$0.30/kWh (higher for pico SHP) [103]. The IRENA study finds LCOE to be highly site-specific but very cost-competitive for developing countries seeking distributed generation (the high end of the LCOE estimation range is lower for developing countries at \$0.11/kWh). The authors conclude that due to the site-specific nature of the data "it is difficult to identify trends" across sites, and reference the lack of a comprehensive dataset [103]. We include the IRENA study here mostly for comparison.

In a 2012 study, Zhang et al. [102] develop LCOE estimates using data from 28 NPD sites in the western U.S. (no additional locational specificity is given) and apply the model toward dams identified by Hadjerioua et al. [8], using data from FERC license orders (FERC eLibrary [128]) for each of the 28 sites. Cost data for NSD sites are estimated using turbine costs from project developers [102]. The projects are limited to the Deschutes and Crooked River basins. LCOE is calculated using Equation 11, and the range of estimates is \$0.022 - \$0.136/kWh. Plant capacities range from 0 – 25 MW for this study, and because the LCOE values are only every plotted (not listed in a data table), it limits our ability to make comparisons.

Zhang et al. observe that their LCOE estimates appear to be driven primarily by site-specific characteristics of head and capacity (like the IRENA report [103]); for future comparisons, they recommend a sensitivity analysis, such as a Monte Carlo simulation, to account for uncertainties (e.g., discount rate, project lifetime) associated with calculating LCOE [102]. Zhang et al. also call for the development of a statistical model to estimate LCOE, but the development of such a model is not within the purview of their 2012 [102] or 2013 studies [13]. Zhang et al. do not indicate a discount rate or project lifetime for this study, so in addition to the plotted LCOE values, we really cannot compare it except to say that the LCOE range falls slightly below the range reported in the IRENA study.

Zhang et al. [13] follow up on their earlier study with a 2013 analysis in conjunction with the development of their ORNL-HEEA model (described in section 2.3.2.). The same 28 sites in Oregon's Deschutes and Crooked River basins are considered using site-specific flow data from Hadjerioua et al. [8] and Energy Information Administration (EIA) price forecasting data for Oregon. Within HEEA, LCOE is calculated using Equation 11, and estimates for the dams 10 MW or less range from \$0.034/kWh - \$1.00/kWh. Zhang et al. discuss LCOE as being a helpful value for judging a site's cost-effectiveness against electricity prices (present and future). While the authors do not cite a specific project lifetime value (number of years), they do report using a discount rate of 6 percent.

Alonso-Tristan et al. [52] use RETScreen4 to calculate LCOE for a single functioning 400 kW (two 200 kW turbines) ROR-type SHP in Spain's Castilla y León region. Though authors do not detail the actual calculation for LCOE (because it takes place within RETScreen4), they do indicate their use of a 4 percent discount rate and 50 year project lifetime. The authors report the RETScreen4-calculated result for LCOE from the single SHP powerplant to be \$0.080/kWh (note: RETScreen4 refers to LCOE as "Energy Production Cost", and the estimated value can be found in the financial viability tab), based on an annual electricity generation value of 17,070 MWh. Equation 11 is likely used in the model. Alonso-Tristan et al. do not provide any information on annuitized costs (though C_{CAP} is mentioned, see section 2.3.4.) or capacity factor, limiting our ability to compare except to say that the value falls on the lower end of ranges mentioned by Zhang et al. [102] and IRENA [103].

In a departure from the usual pattern of bottom-up Excel-based programs, Gagliano et al. [47] use a tool called "MadoWatt", a Matlab-based program developed for engineering-economic hydropower plant simulation and optimization. The authors use the tool (which it sounds like they developed themselves, though this is not ever clarified) to identify the optimal assembly of turbine(s) for refurbishing an existing 77 kW single SHP, which seems to have been disused and in disrepair but not decommissioned. The SHP is part of a larger cascading ROR system (4 SHPs and a water mill, total) in the Madonie mountains in Italy. Gagliano et al. [47] do not calculate LCOE as a part of their single-site study but they do report average values for their study region: \$0.215/kWh for low head (<50m) and \$0.109/kWh for high head (>250m). Gagliano et al. do not report corresponding power capacity ranges for the LCOE values, so it limits their comparability across many of the other studies reported here, especially because the values are on the higher end of the ranges mentioned by Zhang et al. [102] and IRENA [103]. It is unclear if Gagliano et al.'s [47] discount rate or project lifetime applies to the LCOE values (since the LCOE values do not appear to be estimates based on the other project parameters), but we list them in Table 7 anyway. Only the high head sites would be considered economically viable with the reported electricity price of \$0.154/kWh, and because the SHP site has a head of 150m (and the authors never report a site-specific LCOE value), it is unclear if the 77 kW refurbishment project makes this threshold.

Like Alonso-Tristan et al. [52], Adhikary et al. [48] use RETScreen to calculate LCOE for a single 6 MW SHP site in India and find that LCOE is estimated to be \$0.047/kWh. Also similar to Alonso-Tristan, Adhikary et al. [48] estimate LCOE for only a single site, so there is no range of estimates to report. Due to the authors' use of RETScreen4, we can only guess that they used Equation 11 for estimation. The authors conclude that the site is viable because the LCOE is lower than the reported electricity price of \$0.063/kWh. This value falls somewhere closer to the middle of the now-familiar ranges mentioned by Zhang et al. [102] and IRENA [103].

To build on the work of Zhang et al. [13], [102] and create a comprehensive cost dataset for the U.S., O'Connor et al. [11] develop what they call a 'Baseline Cost Model', which includes O&M and LCOE calculations because of the usefulness of the latter as a performance indicator. The authors calculate LCOE using Equation 11, using data from FERC license orders and site characteristic data from Hadjerioua et al. [8], like Zhang et al. [102] (though no specific number of sites or study location is given). Like Zhang et al. [13], O'Connor et al. [11] use a discount rate of 6.2 percent. The range of LCOE estimates is \$0.033 - \$0.235/kWh. O'Connor et al. use LCOE to relate capacity factor and project costs in a way that is easy to understand: rather than interpreting LCOE solely as a site-specific performance indicator to be compared with electricity price, O'Connor et al. recommend that LCOE be considered in conjunction with capacity factor and used to understand cost-competitiveness of the site. For sites with high C_{CAP} values, if the capacity factor is high enough, the LCOE may still be competitive. Likewise, sites with low capacity factors may have high LCOE values because their generation may be contingent upon 'flashy' (high volume, short period, as in storms) or seasonal flows (increased volume during a rainy season). While O'Connor et al. make an effort to plot LCOE value ranges across project types (canal/conduit, low-head NPD, high-head NPD, NSD) using a vertical box-and-whisker plot (useful for indicating data median values and quartiles), their y-axis tick marks are in intervals of \$50/MWh (\$0.050/kWh), making it challenging to pinpoint values. All median values for different SHP types appear to fall between \$100/MWh (\$0.100) and \$150/MWh (\$0.150/kWh). Regardless of what the SHP type-specific median values are, it is clear that canal/conduit sites have the largest LCOE range, and low-head NPD sites have the smallest range. In a graph detailing the mean LCOE value by SHP type, O'Connor et al. [11] show that canal/conduit sites have the highest (\$0.144/kWh), followed by NSD (\$0.135/kWh), low-head NPD (\$0.117/kWh), and high-head NPD (\$0.116/kWh). These mean values certainly fall toward the higher end of the IRENA [103] range.

Carapellucci et al. [45] refer to LCOE as 'unit cost of energy' or 'COE' and calculate it in a manner consistent with Equation 11 for 87 study sites, grouped by region: Aterno-Pescara, Vomano, Tordino, Saline, Sangro, Liri-Garigliano, Foro, and Sinello. In each of the 8 regions, the authors explore LCOE in two scenarios: a pessimistic scenario (based on cost models published by the Polytechnic Institute of Milan, which we were unable to locate using the citation information), and an optimistic scenario (based on Hydro Data Initiative statistics for European SHP, which we were also unable to locate, as the weblink seems to have been broken). The difference between the two seems to be a lower \$/kWh value for the optimistic scenario (lower costs is better) and a higher value for the pessimistic scenario. For the Aterno-Pescara region (with the most economically feasible SHPs), LCOE ranges from \$0.036/kWh - \$0.323/kWh; in Liri-Garigliano, from \$0.048/kWh - \$0.515/kWh; in Vormano, from \$0.060/kWh - \$0.251/kWh; and in Saline, Sinello, Tordino, Sangro, and Foro, LCOE >\$0.120/kWh in almost all cases. The authors identify \$0.180/kWh as a general threshold below which SHP could be considered profitable, so it rules out many of the power plants in most of the regions studied. In the pessimistic scenario, 59 sites are ruled out for development (i.e., LCOE is projected to be >\$0.180/kWh). In the optimistic scenario, only 39 sites are ruled out from consideration.

We graphed the relationship between reported power capacity and LCOE to visually compare site data from some of the studies reviewed here (Figure 8). The highest LCOE value (\$1,008/MWh), reported by Zhang et al. [13], is 31 times higher than the lowest values (\$32/MWh, reported by Balkhair and Rahman [43]). We cannot draw additional substantive conclusions about the cost performance of these projects in comparison to one another, because not only are the regional electricity prices very different from one another, but many LCOE-reporting studies omit electricity price from their study description (unfortunate because the primary value of the LCOE estimate is the ability to compare it to electricity price as a measure of economic viability). The studies left out of this comparison (e.g., Gagliano [47], IRENA [103], O'Connor et al. [11]) did not offer enough project capacity or LCOE data at specific sites to be able to graph them.

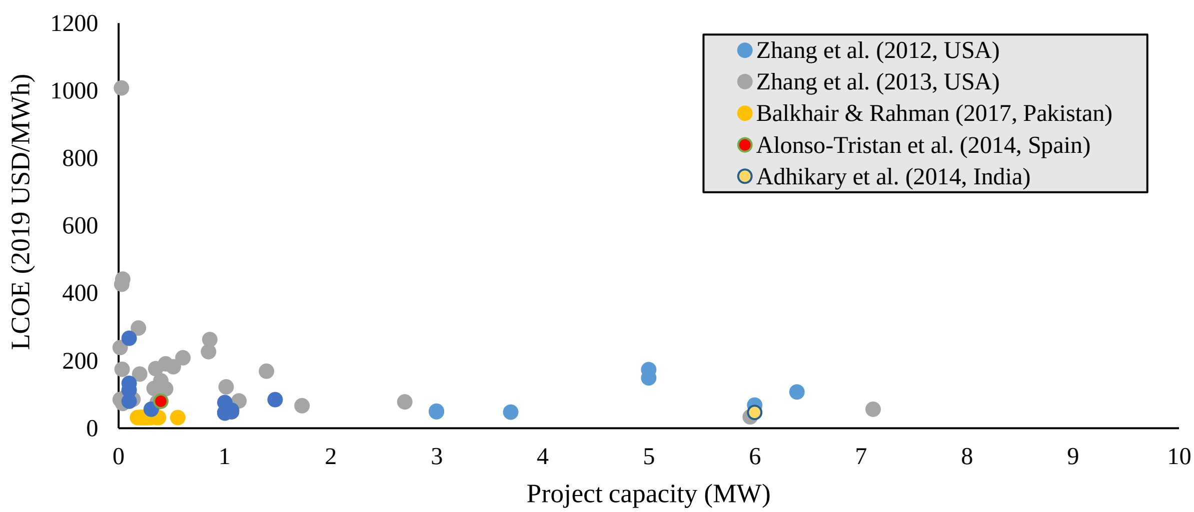

Figure 8. LCOE estimates from relevant studies, compared using power capacity.

2.3.4. C_{CAP} Models

C_{CAP}, defined as spending on acquisition or upgrades to equipment, is a required input to NPV, IRR, BCR, and LCOE calculations. Thirty-two of 35 studies reviewed estimate C_{CAP}. While C_{CAP} is often used synonymously with ICC in hydropower literature, it is important to note that the definition of C_{CAP} is broader than ICC, including the full suite of direct and indirect costs associated with a project. Regression-based models are often used for simple, reconnaissance-level project scoping based on parametric relationships because high capital costs can be a barrier to investment [37]. Most regression-based C_{CAP} estimation studies we review utilize Gordon and Penman's original model of SHP aggregate project costs (Equation 13) [129]. The relationship between cost, power, and net head serves as the basis for most other top-down hydropower production cost models reviewed here (e.g., [9], [34], [41], [94], [102], [119], [122], [130]–[132]). Gordon and Penman's [129] equation (13) was derived in 1979 using data from >100 North American power plants smaller than 5,000 kW (see Cavazzani et al. [34] for a historical summary). The overwhelming trend in the 16 total regression-based and hybrid application/model studies reviewed here is to update the *a*, *b*, and *c* coefficients from Eq. 16 using total project cost data specific to their study area. Different aggregated regression approaches are used by Bockman et al. [37], Aggidis et al. [1], and Filho et al. [35]. Bockman et al. [37] and Filho et al. [35] relate C_{CAP} to anticipated energy production, rather than power capacity, while Aggidis et al. use a modified version of Eq. 16 to estimate both aggregated C_{CAP} and disaggregated costs (total electromechanical, and turbine-specific). Six other studies (e.g. [9], [11], [12], [36], [45], [94]) use the familiar $aH^{b}P^{c}$ form to estimate disaggregated costs; i.e., these studies estimate costs for different types of project components (e.g., civil works, electromechanical equipment) or specific parts (e.g., turbines, generator, penstock). Hall et al. [119] deviate from this general pattern slightly, excluding *H*, and instead relying on *a*, *P*, and *c* to determine the value of various project costs, thereby simplifying Eq. 16 by reducing the overall number of variables. In a break from convention, Kosnik [14], Singal et al. [122], and Cavazzini et al. [34] each take additive linear approaches to disaggregated cost estimation, adding together the individual cost components to achieve a total C_{CAP} estimate.

$C_{CAP}\ (\$) = aH^{b}P^{c}$ (13)

where C_{CAP} = initial capital cost ($); H=head (m); P=power capacity (kW); a, b, and c are coefficients determined through regression.

Like the disaggregated regression models, engineering-economic models add some more nuance to C_{CAP} estimation by adding together components to achieve an overall project cost, where often the final goal of the studies is NPV or BCR (see for example: [10], [13]). Due to their bottom-up nature, engineering-economic models require data for more variables than head and capacity. The models themselves are often ready-made (e.g., ORNL-HEEA, USBR HydroAssesment2.0, HOMER, RETScreen4.0), requiring only inputs from the user. Overall, the range for mean C_{CAP} estimates varies from $201/kW – $35,555/kW, where the highest estimate is 177 times the lowest (as in previous sections, all reported C_{CAP} values have been converted to USD 2019). Excluding the outlier at the top of the range, the top value ($7,493/kW) is still 37 times the lowest. We review all C_{CAP} studies chronologically here (listing mean values where available or calculated from reported data in Table 8), in keeping with the organization of Table 4, and excluding specific sites from our analysis if the power capacity exceeds 10 MW.

Table 8. C_{CAP} estimates from select regression-based and engineering-economic estimation studies for SHP. Values converted and escalated to USD 2019.

Author(s)	Mean Power Capacity (kW)	Mean CCAP Estimate ($)	Mean CCAP ($/kW)
Singal et al. [122]	4000	$7,612,938	$2,483
USBR [10]	971	$5,704,413	$16,941
Zhang et al. [13]	933	$3,445,893	$7,493
Zema et al. [94]	174	$676,851	$3,353
Balkhair & Rahman [43]	272	$54,614	$201
Cunha & Ferreira [49]	1900	$5,697,677	$2,999
Park et al. [54]	695	$1,440,540	$3,131
Kosnik [14]	100-1000	$5,188,680	$35,555
Cavazzini et al. [34]	510	$227,794	$700
Filho et al. [35]	4713	$11,498,933	$2,398

Hall et al. [119] from Idaho National Laboratories (INL) estimate Eq. 13 coefficients *a* and *c* in a modified version of Eq. 16 for 22 disaggregated least squares regression models for NSD and NPD project costs (direct and indirect): $C = aP^b$ (Appendix E). Independent variables in disaggregated cost regressions include construction costs; licensing and permitting; fish and wildlife mitigation, recreation mitigation, historical and archaeological mitigation, water quality monitoring; fish passage; fixed and variable O&M; turbine unit upgrade costs for Francis, Kaplan, and Bulb types; and generator unit upgrade. To determine coefficients, Hall et al. use construction data from the Energy Information Administration (EIA), detailing costs for 695 U.S. plants built between 1990 and 2000 (1-1300 MW), and FERC license data. Median C_{CAP} ranges from $1,571/kW to $4,713/kW (converted to 2019 USD), but it is unclear how C_{CAP} is estimated, given the disaggregated equations reported in the Hall et al. study. We assume that O&M costs are excluded from the dollar estimates reported and that CCAP represents some combination of construction, licensing, and fish passage costs.

Bockman et al. [37] estimate C_{CAP} as a function of energy production, *m* (Equation 14), for use in the maximization of NPV for three SHP sites (described in section 2.3.1.). The authors do not disclose the actual value for C_{CAP}, again limiting our ability to compare results from Eq. 14 with the other models reviewed to determine whether Bockman et al.'s estimates are comparative outliers or whether they fit into the aforementioned range. Moving to the opposite end of the problematic reporting spectrum, Pletka and Finn [121] report estimates but do not offer a specific equation for C_{CAP} calculation. Their data come from Hall et al. [119], so Pletka and Finn may have used some collection of the Hall et al. equations to calculate their 'all-in capital cost' values (i.e., C_{CAP}). Pletka and Finn's C_{CAP} estimates range from $764/kW (for powered dam capacity expansion) to $238,334/kW (for a ROR NSD project) for all (20,384) projects in the study (U.S. and Canada). The range was smaller for U.S. hydropower, where C_{CAP} ranged from $777/kW - $4,385/kW. While we know the overall study is a bottom-up study, we do not know whether C_{CAP} is estimated using regression or engineering-economic methods.

$$C_{CAP}(m) = Ae^{bm} \tag{14}$$

where A and b are constants and e = natural log base.

Aggidis et al. [41] use two aggregated regression models to estimate C_{CAP}, one for each of two different head ranges (2 – 30 m, and 30 – 200 m), based on a 2013 Salford engineering report on SHP potential in the UK (unable to locate), where the relationship between Eq. 16 power and head parameters and coefficients is slightly reorganized: $a(P/H^c)^b$. C_{CAP} estimates range from ~\$156,000 – ~\$ 3 million (based on graphed results, as no actual values were reported) for projects from 25 – 990 kW. Though they use two different models for C_{CAP} estimation, they do not distinguish between models in their results, nor do they report an R^2 value to indicate model fit. Aggidis et al. do report that their estimates are within 25 percent of the original Salford report estimates. Interestingly, Aggidis et al. also use disaggregated regression models to estimate electromechanical equipment costs and turbine-specific (Francis, Kaplan, Pelton) costs using proprietary manufacturer data. The relationship between power and head parameters and coefficients for these disaggregated cost equations is the same as with their C_{CAP} equation. Aggidis et al. do not share actual dollar values for disaggregated turbine and electromechanical equipment costs, nor do they share R^2 value; rather, the purpose of the activity seems to have been to compare their results with estimates from Papantonis [130] and Ogayar and Vidal [131]. However, no percentage of difference results were reported.

Singal et al. [122] use a disaggregated regression approach to estimate piecewise all of the civil works (powerhouse, powerhouse building, diversion weir/intake, power channel, desilting chamber, forebay and spillway, penstock, and tailrace) and electromechanical components (turbines, generator, electrical/mechanical auxiliary, transformer and switchyard equipment) of a ROR SHP using 11 component-specific equations, each a corresponding version of Eq. 13. For each of these disaggregated regressions, *a*, *b*, and *c* are adjusted for each component. Then, the electromechanical component costs are summed together, while the civil works component are summed together. Next (Equation 15), the joint sum is multiplied by a coefficient to account for variations in costs (i.e., indirect costs are estimated as an additional 13 percent of combined civil works and electromechanical equipment costs), for a total C_{CAP} [40], [122]. The data from which the set of regression models were developed come from Singal's Ph.D. thesis and were inaccessible online. It is important to note that Eq. 15, unlike other disaggregated regressions discussed here, is a complete representation of C_{CAP}, because it takes into account indirect costs. Reported C_{CAP} estimates range from \$1,577/kW to \$3,232/kW. Singal et al. [122] reiterate results from Singal and Saini [40] reporting that C_{CAP} is broken down as follows: 54.5 percent electromechanical equipment, 34 percent civil works, and 11.5 percent 'other' (for heads 3m or less). The authors do not indicate what goes into 'other' but based on their discussion of Eq. 15, we suspect that 'other' refers to indirect costs captured by the coefficient (1.13). Other studies by these authors ([40], [120]) reiterate the regression models used and the percentage of C_{CAP} distribution, highlighting the correlation between disaggregated costs (e.g., electrical/mechanical auxiliary, transformer and switchyard equipment) and different inputs like head, and capacity.

$$C_{CAP} = 1.13(C_{civil} + C_{electro}) \tag{15}$$

where C_{civil}=sum of civil works costs; $C_{electro}$ = sum of electromechanical equipment costs.

In a mixed model and application study, Kosnik [14] builds on studies from the USDOE examining the technical viability of 125,000 NSD sites for SHP (between 10kW and 30,000 kW, the previous higher bound for SHP in the U.S.) in the U.S. and explores the economic viability of site development. Kosnik [14] compares estimates from three different costing models: 1) RETScreen4, a bottom-up model from Natural Resources Canada (NRC), 2) NorwegianMacro, a bottom-up model from the Norwegian Water Resources and Energy Directorate (NWRED), and 3) Kosnik's own additive linear regression-based C_{CAP} estimate [14] (Equations 16-20). Equation 17 is analogous to Equation 13, and the rest (Eq. 16, 18 – 20) are an effort to capture the additional cost of transmission infrastructure in NSD project costing. It is important to note that Kosnik's regression does not include indirect costs and cannot, therefore, be interpreted as a complete estimate for C_{CAP}. The site data come from a USDOE study. Interestingly, Kosnik does not report the estimated results using Eq. 20, instead vaguely stating that the values fall somewhere between RETScreen and NorwegianMacro estimates [14] (Table 9). Similarly, Kosnik does not report an R^2 value for the linear additive regression model, so it limits our ability to compare it with others like it (e.g., Singal et al.[122], Cavazzini et al.[34]). RETScreen4 is a proprietary bottom-up Excel macro that generates estimates for C_{CAP}, as well as other project attributes like turbine runner diameter (using parameters/inputs from Eq. 18 – 20). Kosnik describes the RETScreen4 estimates as an upper bound for the overall set of results because the project costs include life cycle costs (unclear how this is calculated in the program) and feasibility study (or "soft") costs, in addition to construction cost [14].

$$C_{CAP} = m + h + k + t + \varepsilon \quad (16)$$

$$m = aP^b H^c \quad (17)$$

$$h = \left(\frac{\beta_0 \rho x^{\beta_1} z}{1000}\right) \quad (18)$$

$$k = (\gamma_0 + \gamma_1 d + \gamma_2 z + \varepsilon) \quad (19)$$

$$t = (\delta_0 + \delta_1 q + \delta_2 z + \varepsilon) \quad (20)$$

where m=construction costs ($); h=penstock costs ($); k=switchyard equipment costs ($); t=transmission line costs ($); ε =error term; ρ=penstock length (meters); x = head; z = power; d=voltage (VAC); q=transmission line length (meters);a, p, c, γ, δ, and β are all estimated through regression.

Table 9. Upper and lower C_{CAP} estimate bounds. Source: Kosnik [14], converted to USD 2019.

Type SHP	Power Capacity Range (kW)	Number of sites	Model	MAX ($/kW)	MEAN ($/kW)	MIN ($/kW)
Micro	<100	1691	RETScreen	313334	69793	4618
Micro	<100	1691	NorwegianMacro	361894	69547	3651
Mini	100 - 1000	28616	RETScreen	7155574	21286	1602
Mini	100 - 1000	28616	NorwegianMacro	496929	8104	885
Small	1000 -30000	5427	RETScreen	1458213	9769	748
Small	1000 -30000	5427	NorwegianMacro	198713	3069	67

NorwegianMacro is likewise a proprietary bottom-up Excel macro that uses hydropower construction cost relationships (direct and indirect) for small-scale facilities published by the Norwegian Water Resources and Energy Directorate (NWRED). Unlike RETScreen4, we were unable to locate the actual model or the documentation from NWRED, so we rely on Kosnik's description to compare the model. As with RETScreen, Kosnik uses the parameters/inputs from Eq. 21-24 in NorwegianMaco to calculate C_{CAP} results. These estimates do not include life cycle or feasibility study costs as the RETScreen estimates do, so Kosnik describes NorwegianMacro estimates as lower bound [14]. Kosnik [14] concludes that overall, C_{CAP} was most sensitive to changes in head and flow (notably not power capacity), even when considering the other site-specific parameters more closely tied to facility accessibility (i.e. the ruggedness of the terrain and proximity to existing roads and transmission lines). Kosnik cautions that sites with lower technical potential (i.e., with lower projected power capacity) will likely be more expensive, due to nonlinear economies of scale.

Though the USBR study [10] covers 530 sites across the Western United States, the authors focus on 186 SHP sites with existing non-powered dams and canal/conduit sites for C_{CAP} estimation. Using their HydroAssessment2.0 tool, C_{CAP} ('plant cost') is broken down into civil works, electromechanical, and associated regulatory fees (permitting, licensing, provisions for fish passage, and more), not unlike the setup developed by Hall et al. [119]. To calculate indirect project costs, HydroAssessment2.0 breaks up indirect project costing calculations by category: contingency, sales tax, engineering and construction (Appendix E) [124]. Indirect project costs are estimated as a percentage of the total construction cost, so we know that C_{CAP} estimates include both direct and indirect costs. Reported C_{CAP} values range from \$1,842/kW - \$111,653/kW. Though they estimate component costs, the USBR paper does not report component estimates. Like Hall et al. the USBR study considers licensing, permitting, and fish passage provisions explicitly. Like Singal et al. [122], the study reports cost uncertainty (i.e., contingency, engineering) as an additional percentage added to the projected total direct cost. The USBR paper adds 20 percent contingency for direct costs (mainly construction) and then an additional 15 percent on top of the total (with direct cost contingency added) to account for uncertainty from engineering and construction management (i.e., indirect) costs. The 15 percent of total direct costs for indirect cost estimation is somewhat consistent with Singal et al.'s 13 percent.

Like Kosnik [14], Alonso-Tristan et al. [52] use RETScreen4 to estimate C_{CAP} for the single Spain SHP site using site-specific data collected from the private firm that owns the existing diversion facility. The authors report that the actual installation cost was ~\$1.6 million, which translates to \$3,958/kW for the 400 kW facility. The authors do not report the RETScreen-generated C_{CAP} estimate for comparison; rather, they report the component percentage of C_{CAP} like Singal et al. [122] and Singal and Saini [40]: 56 percent civil works; 39 percent electromechanical equipment; 4 percent feasibility, development, and engineering; and 1 percent contingencies. The civil works and electromechanical equipment percentages are slightly higher than Singal and Saini's [40] values, so the indirect cost portion is much lower (recall, Singal and Saini estimated indirect costs to compose 11.5 percent of the total C_{CAP} value.

In an aggregated linear regression-based C_{CAP} model study, Zhang et al. [102] from ORNL calculate C_{CAP} for 42 sites with existing infrastructure (i.e. NPDs & canals/conduits). They use two of Gordon and Penman's [129] originally proposed coefficient values for Eq. 16, b (-0.35) and c (0.7), and update only a (110,168) to reflect price escalation (e.g., from 1979 to 2012 USD), using FERC license data [12]. C_{CAP} estimates here are strictly reflective of ICC costs (making them incomplete estimates) and range from \$7,157/kW-\$9,964/kW for NSD sites, and \$5,419/kW - \$7,749/kW for NPD sites (interestingly, the NSD values seem to be borrowed, escalated from an earlier report by Hatch Energy [133] for Natural Resources Canada, rather than a product of the authors' analysis). The R^2 value for the C_{CAP} regression is 0.6, indicating that the model explains only 60 percent of the variation. The authors report that they tried other regression estimation approaches (simply identified as non-linear, with no further specificity), but while the model fit was better (R^2 value between 0.9 -1), the error range was too large to consider using the non-linear model. Also, while Zhang et al. use the familiar approach to regression-based estimation, they caution about interpreting the results from this and other studies too broadly (i.e., to different types of sites or different ranges for power capacity and head). Zhang et al. strongly advise using a large data sample for determining coefficients through regression, because the estimates tend to be too site-specific otherwise.

In their 2013 study, Zhang et al. [13] estimate C_{CAP} for SHP sites in Oregon using their HEEA tool. It is unclear what Zhang et al.'s exact cost calculations with ORNL-HEEA are, but the authors report that the tool requires the following inputs: site type (NSD, NPD, or canal/conduit), penstock length, transmission line length and voltage, an environmental indicator (this value triggered additional up-front mitigation costs, pulling from Hall et al. [119]), and finally, real estate and water rights purchasing costs. C_{CAP} estimates are inclusive of indirect costs and range from \$1,175/kW – \$35,487/kW. It is important to note that Zhang et al. produced two estimates (with transmission, and without transmission) for sites where transmission connection was needed because transmission interconnection could increase project costs by up to 90 percent. Like the USBR study [10], Zhang et al. [13] estimate contingency, estimated as 8 – 12 percent of construction costs including sales tax (the authors report that the exact contingency value relates to project scale, with no additional information), and added to the total, on top of state sales tax. All indirect costs are estimated separately, and the equations for these appear to come from Hall et al. [119] (i.e., environmental mitigation, licensing, and engineering costs). Unique to the HEEA model, Zhang et al. [13] also distinguish between electromechanical parts manufactured domestically, in Canada, or in China. In all cases, we have selected the lowest project cost estimates, which usually included parts from Chinese suppliers.

More recently, a USACE report [9] details C_{CAP} estimation for 223 of the 419 total USACE-owned NPD sites, 12 of which can be considered SHP. For sites with ≥3 years of daily flow time series data, a flow exceedance curve is used to estimate site power capacity [9], which in turn feeds into C_{CAP} direct and indirect cost component estimates. Direct costs for turbines and generator, as well as indirect costs for licensing, fish and wildlife mitigation, recreation mitigation, historical and archaeological mitigation, water quality monitoring, and fish passage are estimated in the same way as Hall et al. [119], updating only coefficient *a* from the earlier study (like Zhang et al. [102]), as a reflection of escalated costs. The USACE report uses USBR [124] formulas for the remaining C_{CAP} components: direct costs for civil works, mechanical and electrical balance of the plant, and transformer cost; as well as indirect costs for contingency, sales tax, and engineering and maintenance (as in the ORNL-HEEA model). Unlike the equations borrowed from Hall et al., the USACE report does not escalate the USBR equations, because the values are representative of percentages of other cost estimates (i.e., contingency is estimated as 20 percent of construction costs). Though the USACE report details cost equations thoroughly, the authors do not actually list C_{CAP} estimates for the 223 sites. Instead, they report only IRR and BCR.

Motwani et al. examine [51] the cost-effectiveness of using a pump-as-turbine, which is described as a cost-effective alternative for SHP projects with power capacities up to 100 kW, intended for electrification of rural communities with unreliable electricity. The bottom-up study is on LCOE comparison between the pump-as-turbine and conventional turbines, which Motwani et al. refer to as a justification for not considering civil works or indirect costs. As such, this an incomplete representation of C_{CAP}, based solely on the cost of the turbine(s). Like Alonso-Tristan et al. [52], Motwani et al. do not report an actual estimate of C_{CAP} for the 3 kW project, but rather give the installation cost data points given by the turbine manufacturer: $472 total for the pump-as-turbine, and $3,775 total for the Francis turbine. Both cost data points sit on the low end of our C_{CAP} spectrum, but again, they are an incomplete representation of C_{CAP}, and are not actual estimates but rather values provided by the manufacturer, so our ability to compare this study with others is limited.

Like Motwani et al. [51], Kusakana [50] explores unconventional hydropower options for remote, rural communities not yet connected to the grid. Instead of different turbine alternatives, Kusakana compares HKT turbines with battery (BT) storage as an option in comparison with other small (4 kW -15 kW) hybrid generation and storage systems (i.e., HKT with diesel generator (DG) and BT; HKT with solar photovoltaics (PV), DG, and BT; HKT with PV and BT; PV and DG with BT; PV with BT; and wind turbine) using bottom-up proprietary software HOMER. HOMER, like RETScreen, is a program designed to simulate and optimize power production given site characteristics and different technology options (in this case, multiple generation and storage technologies instead of hydro turbine types). The HKT is intended to be used in a modular way, so the units are 1 kW each, with an expected power capacity of 4 kW when used alone (with a component cost of $8,099/kW), though project power capacity is substantially increased with the addition of a battery (7 kW). Focusing on project options involving HKT, HOMER-estimated C_{CAP} is $40,606 total for HKT with BT; $41,654 for HKT, PV, and BT; $31,305 for HKT, DG, and BT; and $35,414 for HKT, PV, DG, and BT. HOMER is proprietary and expensive, so we were unable to explore the model to understand how the C_{CAP} estimate is made. Kusakana does not report the equation used, either.

Cunha and Ferreira [49] estimate C_{CAP} in a study whose main purpose was a risk (i.e., sensitivity) analysis on NPV estimates using @Risk software and a bottom-up cash flow model, so the actual C_{CAP} calculation is never identified. Cunha and Ferreira offer component estimates, where construction (i.e., civil works) costs were based on market conditions and electromechanical component prices were identified by manufacturers Summing the component costs achieves a total project cost of $4,286,868, which is ~$2,256/kW for a project of 1,900 kW. In this case, C_{CAP} is considered complete, because it includes studies, licensing, consulting, and other indirect costs. Cunha and Ferreira test the sensitivity of NPV to percentage changes in C_{CAP} and find that a 5 percent increase in C_{CAP} corresponds to a $216,985 decrease in NPV. Cunha and Ferreira also parse out the sensitivity of NPV to individual component cots and find that civil works and electromechanical equipment are the most uncertain C_{CAP} components (i.e., components with the greatest impact on the mean NPV estimate). This result makes sense, given what we know from Singal et al. [122], Singal and Saini [40], and Alonso-Tristan [52] about civil works and electromechanical equipment as the two largest proportions of C_{CAP}.

Adhikary et al. [48] use RETScreen4 to analyze a 6000 kW SHP in a bottom-up study. Like other studies using RETScreen, no equation is indicated for the estimation of C_{CAP}, but the authors report a complete C_{CAP} estimate of $14,372,252 total, or $2,395/kW. Adhikary et al.'s estimate is below the mean estimate ($3,075/kW) from Kosnik for sites 1000 kW – 30,000 kW, but it sits comfortably in the range for what Kosnik considers 'small' (see Table 9). Adhikary et al. also report that electromechanical equipment (called 'power system') composes 35 percent of C_{CAP}, while indirect costs compose 12 percent. The remaining 53 percent is labeled as 'balance of system and miscellaneous' and is never clearly defined (though we suspect that it is mostly civil works costs). This breakdown of C_{CAP} is reminiscent of Singal et al. [122] and Singal and Saini [40], though these studies are neither mentioned nor cited. Adhikary et al. do cite the work of Alonso-Tristan et al. [52], whose percentage of C_{CAP} breakdown results are comparable.

In another study out of ORNL, O'Connor et al. [123] develop regression equations for aggregated and disaggregated C_{CAP} for multiple types of SHP projects using the same format as Equation 13, again updating coefficients *a*, *b*, and *c* as appropriate. The set of regressions is collectively dubbed the 'Baseline Cost Model' (Appendix E). O'Connor et al. use capacity and head data from FERC licensing documents, the Electric Power Research Institute (EPRI), Industrial Info Resources (IIR), EIA, and additional sources. The dataset includes 31 NPD, 18 NSD, 20 canal/conduit, 4 turbine unit addition, and 8 generator rewind construction-stage projects. The authors do not specify the state, region, or even country from which the data are drawn, except for canal/conduit and generator rewind projects, which were all located within the U.S (no generator rewind data from Southeast or Midwest regions). O'Connor et al. include construction and equipment costs in C_{CAP} estimation. They report that average C_{CAP} is the lowest for the average NPD project, which is estimated to cost \$4,271/kW. NPD and canal/conduit projects (mean cost \$4,812/kW) are both less expensive on average than NSD projects, (mean cost \$5,177/kW) according to O'Connor et al.'s analysis. Other cost estimates from this study include turbine unit addition (i.e., capacity expansion, mean cost of \$2,466/kW), and generator rewind (i.e., refurbishment, mean cost of \$125/kW). Like the earlier ORNL study by Zhang et al. [102], O'Connor et al. note that all estimates are subject to economies of scale (head height, power capacity) and that actual costs vary considerably based on site characteristics.

Carapellucci et al. [45] use separate (depending on head) aggregated C_{CAP} regressions for SHP cost estimation at 87 NSDs, following the same $C = aP^c$ format as Hall et al. [119]. Unique to this study, Carapellucci et al. describe an optimistic and pessimistic scenario for project cost estimation, where the pessimistic scenario breaks C_{CAP} into two types: low head (<80m), and high head (>80m). The optimistic scenario breaks C_{CAP} into three categories: high (>100m), medium (30 – 100m), and low head (<30m). The authors do not report C_{CAP} estimates because they were not the end goal of the study; rather, the focus of the study is on estimating LCOE to compare project feasibility. This lack of C_{CAP} results makes this study challenging to compare to others.

Zema et al. [94] use Eq. 16 to estimate C_{CAP} for projects in an irrigation system (i.e., canal/conduit sites) as a part of their NPV study [94]. The main difference between this study and the other costing studies listed in Table 8 is that Zema et al. estimate total C_{CAP} for 3 SHP canal/conduit schemes, constructed as a series of projects diverting water for hydropower generation via pipeline, generating at multiple plants along the same pipeline before connecting to another pipeline for additional generation or an end consumptive use. Like Singal et al. [122], Zema et al. describe C_{CAP} as the sum of electromechanical equipment, civil works, engineering, power transmission line connection, and administrative costs; however, Zema et al. define the total C_{CAP} estimation as an aggregated cost regression for the entire irrigation system, consistent with the methodological choice of many other studies we review. C_{CAP} estimates for the three irrigation schemes are $2,312/kW, $3,039/kW, and $4,708/kW, respectively. The highest estimate is closest to what O'Connor et al. report for canal/conduit project unit costs.

Reminiscent of Kosnik's [14] additive linear approach, Cavazzini et al. [34] use a correlation that uses a different functional form from the traditional Eq. 13 (Equation 21). Cavazzini et al. [34] review[9] and critique studies using Eq. 13 as data-poor and they compare their estimates (derived from a dataset of 49 SHPs in Italy, Guatemala, and Spain) with estimates from seven previous (e.g., [41], [55], [129]–[131]) studies, showing how their model competes for accuracy. Cavazzini et al. break down the traditional electromechanical equipment cost category into separate electrical (iP^j) and mechanical terms (dH^e, fQ^g) within the regression, using the familiar flow, head, and power capacity parameters with a new set of correlation constants (Equation 21). Then, Cavazzini et al. use a computational optimization method (called Adaptive Search Diversification and Particle Swarm Optimization, or ASD-PSO) Their estimates for Pelton and Francis turbines are based on 13 existing SHP plants using Pelton turbines in Italy (72 kW – 1502 kW) and 12 existing SHP plants using Francis turbines in Italy and Guatemala (148 kW – 2,459 kW). They also borrow equipment cost data for the Kaplan estimates from Ogayar and Vidal's Spain study (100 kW – 1500 kW) [132]. Cavazzini et al. then compare their C_{CAP} estimates, which range from $304/kW to $1,882/kW, with estimates produced using from the following versions of Eq. 13: Gordon and Penman [129], Aggidis et al. [41], Ogayar and Vidal [131], Papantonis [130], and others. The percentage error between estimates generated by Cavazzini et al.'s approach and actual SHP cost data range from -27.5 percent to 21.3 percent.

$$C_{CAP} = dH^e + fQ^g + iP^j + k \qquad (21)$$

where H= net head (meters), Q = design flow rate (liters/second), P = power (kW), and d, e, f, g, i, j, k are correlation constants.

[9] Elbatran et al. [134] likewise review Ogayar and Vidal's [131] turbine-specific C_{CAP} equation, but unlike Cavazzini et al. [34] they do not propose new regression coefficients or functional form. Their study is strictly a review, so we exclude it from our analysis.

Using a more site-specific approach than Zema et al. [94], Balkhair and Rahman [43] estimate C_{CAP} for each of 20 SHP sites along an irrigation canal in their power production and LCOE study. Unfortunately, Balkhair and Rahman do not report the method used to estimate C_{CAP}. Likewise, their data collection was focused on hydrological data, so it is unclear whether the C_{CAP} values were reported by hydropower operators or estimated. The authors report that C_{CAP} unit costs are approximately \$201/kW (which we calculated based on total project C_{CAP} and power capacity for ease of comparison with other results reported here), with totals ranging from \$35,932 (179 kW capacity) to \$112,685 (561 kW). The C_{CAP} unit costs are quite low, but again, we estimated them for comparison, so the CCAP estimates reported by Zema et al. are likely incomplete.

Filho et al. [35] use an aggregated approach to estimating C_{CAP} and substitute *H* and *P* for aspect factor (*AF*, a value expressed as a function of *H* and *P* and given in rotations/second, related to the specific speed of the turbine) in their equation (Equations 22-23). Filho et al. follow the familiar pattern of identifying the regression coefficients based on local site data for 21 Brazilian SHP projects. The data are proprietary, so the site names are given only as SHP 1, SHP 2, and so forth. Like Cavazzini et al. [34], Filho et al. [35] compare and contrast their estimates, which range from \$1836/kW to \$2876/kW, with estimates produced by versions of Eq. 16: Singal and Saini [40] and Mishra (we were unable to locate this cited Ph.D. thesis). Filho et al. find that their C_{CAP} estimates for the original SHP cost data used to develop the regression have a relative deviation that ranges from 0.4 – 57.8 percent, and from 0 – 53.6 percent when used to estimate project costs using head, flow, and power capacity data from Singal and Saini. Like the studies by Cavazzini et al. [34], Kosnik [14], and Bockman et al. [37], this study ([35]) is an exception to the aggregated regression-based approach but is unclear if this new approach is an improvement over the more traditional updates to Eq. 13 based on country and site-specific parameters.

$$C_{CAP} = aAF^b \tag{22}$$

$$AF = f(H,P) = 1821.43\left(\frac{P^{0.5}}{H^{1.25}}\right) = \frac{n_{qA}}{n} \tag{23}$$

where H = gross head (m); P= power capacity (MW); n_{qA} *= turbine specific speed; and n = turbine rotational speed; a and b are coefficients determined through regression.*

As in our exploration of published estimates of BCR, LCOE, and NPV, we graph reported C_{CAP} with power capacity to compare studies (Figure 9). The highest reported C_{CAP} estimate is \$57.5 million/MW (Kosnik [135]), and the lowest is \$0.2 million/MW (Balkhair and Rahman [43]). C_{CAP} decreases substantially with increases in project power capacity, with reported estimates all below \$10 per MW for projects of 2 MW or more.

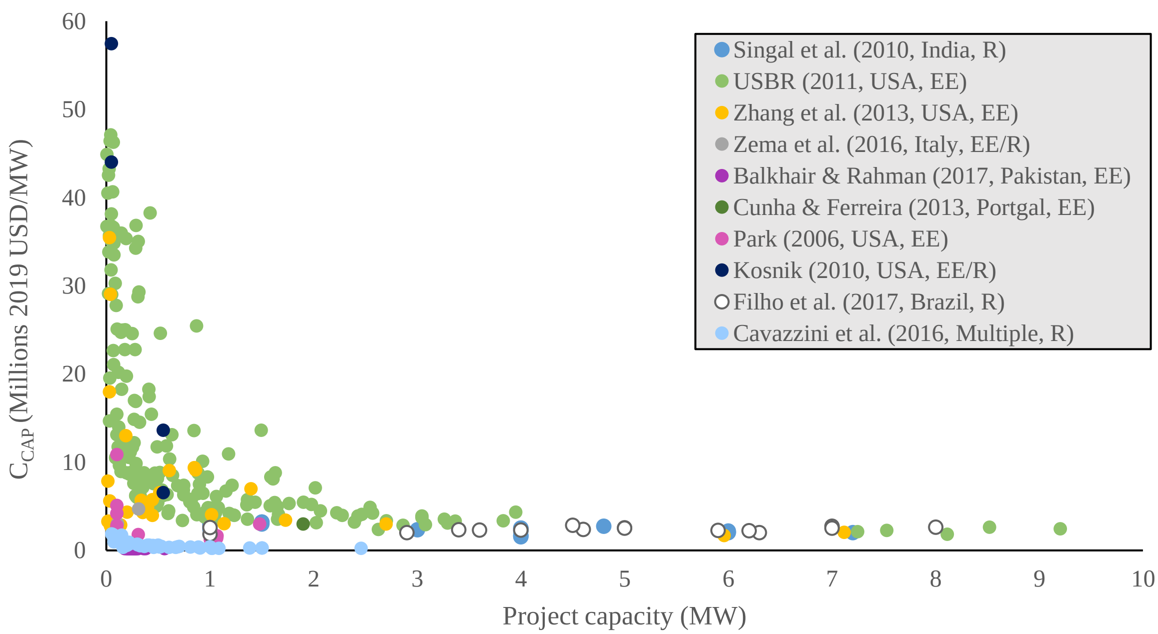

Figure 9. C_{CAP} estimate comparison from reviewed studies.

In summary, regression-based models for SHP project costing are suitable for project cost estimation when identifying potentially viable development sites in a broad-brush way, because they rely on a small set of project parameters. Regression-based aggregate cost modeling provides a means of estimating C_{CAP} as a function of power capacity and head, two parameters that drive site-specific differences in capital cost. Regression-based models are developed using linear regression, and typically require large-N (number of projects) cost datasets to ensure appropriate coefficient identification. Aggregated regression-based models are elegant in their simplicity, making them particularly useful in quickly establishing a maximum investment threshold (i.e., a site must be below a certain C_{CAP} value) and excluding sites from further exploration. Note: due to their simplicity, aggregated regression models may be prone to error. Zhang et al. warn that lower-head SHP project costs may be more sensitive to site-specific features (e.g. existing dam infrastructure) than higher-head project costs [102]. Disaggregated approaches appear to be popular as a more site-specific approach: seven studies estimate C_{CAP} for different turbine types [9], [12], [34], [41], [119], [131], and some break down C_{CAP} by category (e.g. civil works, electromechanical, transmission) [9], [41], [122], [132]. Disaggregated approaches may not represent the total C_{CAP} value; more often than not, we see disaggregated approaches focused on turbine costs. Where disaggregated approaches do estimate complete C_{CAP} (including soft costs), they are useful in providing nuanced information about projected expenditures; however, disaggregated regression models do require more data. Zhang et al. warn that electromechanical equipment is the cost category most sensitive to head and capacity parameters [102].

Bottom-up models, like disaggregated regression-based approaches, use multiple user-specified inputs, and so are better equipped to handle the site-specific nature of civil works (e.g. penstock, tailrace) and electromechanical equipment (e.g. turbines, generator) costs that depend on unique site characteristics. Bottom-up models are typically based on heuristic cost relationships, so for NPDs, powered dams, and canal/conduit sites (i.e., sites that already have dam infrastructure in place) bottom-up models are a more sophisticated choice for project viability assessment across multiple states or multiple projects within a single state. We discussed bottom-up cash flow models, as well as proprietary software such as HOMER, MadoWatt, RETScreen4, NorwegianMacro, and open access models such as ORNL-HEEA, and HydroAssessment2.0.

Other benefits of the publicly available models include (1) clarity about price escalation method and dollar-year used in reporting, (2) thorough comparison between previous bottom-up cost estimation models, and (3) potential for replicability due to the free and open-source nature of the model release.

2.4. Discussion

Dam decisions, whether carefully planned or opportunistic, physically shape riverine habitats, change resource flows, impact economic development, and alter the cultural heritage of the communities through which rivers run. Dam decisions also impact the availability of low-cost hydroelectricity to communities in the surrounding regions. In this review of the literature, we identified disagreements in the SHP literature and drew a more complete picture of the techno-economic considerations for SHP development in the Northeast, specifically. We divided our discussion of SHP costing into three general categories: 1) performance assessment (NPV, IRR, BCR, LCOE), and 2) C_{CAP} to bring some clarity to areas that we perceived as opaque or ill-defined in the literature. We compared and contrasted studies reporting project performance assessment metrics which (to our knowledge) had not yet been done systematically in the academic literature. We also broke down our discussion of C_{CAP} by regression-based estimation models and bottom-up models and then subdivided each model type by direct and indirect cost estimation, to explore the advantages and disadvantages of each.

Across all studies and model types, data availability may be an issue (see for example Zhang et al. [12]), where studies doing hydropower costing are examining only a single site (this is the case in many of the studies reviewed here) or rely on proprietary datasets (e.g., from a manufacturer) or models (e.g., RETScreen, HOMER). To get around the data issue, many studies use top-down approaches that require only power capacity and head information. Kelly-Richards et al. critique the top-down approach [21], suggesting that regression-based C_{CAP} estimation is not enough on its own to determine a project's impact on the landscape and the people who depend on the river or tributary as a resource. We agree with this critique but argue that regression-based models are still useful when applied to technical power capacity data for NSD sites to establish a threshold (i.e., below a certain C_{CAP} value) excluding sites from further exploration. Regression-based models should be used one step of several in scoping, before multi-criteria approaches that incorporate social and cultural considerations. A total of 12 studies differentiate top-down C_{CAP} estimates by turbine type or equipment category (e.g., [32], [34], [35], [41], [122]), which demonstrates an interest in producing more accurate scoping estimates, at least for NSD sites. Hall et al. [119] and O'Connor et al. [123] were the only two studies to attempt differentiation between NSD, NPD, and powered dam costs when using a top-down approach. While some researchers compare their top-down estimates to other estimates from previous studies in different locales (e.g., [32], [34], [35]), their sensitivity analysis begins and ends at an acknowledgment of the percentage difference between results.

Bottom-up studies offer no additional clarity on the matter. We find this curious, given that bottom-up models pay attention to specific project component costs, site-specific parameters (including time series of hydrologic flows), and year-over-year project cash flows. Like top-down studies, bottom-up studies seem to ignore potential sources of uncertainty in NPV estimation (e.g., discount rate, electricity price), even though NPV estimates are susceptible to changes in electricity pricing (because revenues from electricity sales account for most, if not all, project benefits), and the discount rate is likewise a known unknown [12]. Other sources of uncertainty include development incentives (e.g., federal tax credits) which may offset high upfront costs or even provide a secondary income stream but may differ significantly by state (see, for example: [136], [137]). The variability of key project parameters (i.e., inputs, e.g., discount rate, electricity price, incentives) presents a clear need for sensitivity analysis. Most studies we review do not report any form of sensitivity analysis on key project parameters, whether as simple as best-worst-most likely, or as thorough as Monte Carlo simulation. Sensitivity analysis is critical for communicating to the reader how much the model results are impacted by input uncertainty.

2.4.1. Model Recommendation for Northeastern U.S. SHP

Due to their potential for accommodating site-specific characteristics, equipment differences, seasonal variation in flows, and indirect costs, models we identify as "bottom-up" or engineering-economic models may be better suited for the Northeast than regression-based or "top-down" models. Site differences matter everywhere, but perhaps especially in the Northeast, where many existing NPDs and licensed powered dams in the region limit the application of regression-based models designed to estimate C_{CAP} for NSD development.

RETScreen and HOMER appear to be the industry standard for bottom-up cost estimation. A newer version of the RETScreen software, RETScreen Expert[10], is an upgrade from RETScreen4, which was Excel-based (the RETScreen Expert version is a standalone software program). While this tool has potential for international application across different renewable technologies, and there are a handful of case studies/templates for SHP projects (220 kW to 8,800 kW) for run-of-river and impoundment/reservoir sites, users need to subscribe and pay to use the "Professional" version of RETScreen [11]. Natural Resources Canada does solicit outreach from educational institutions (i.e. there may be potential for free or reduced pricing). 'Hydro systems' is a HOMER add-on module ($75), thereby increasing the cost of an already expensive software. Though HydroAssessment2.0 is free, it is built specifically to accommodate Reclamation-specific projects and does not allow flexibility for different hydropower schemes (run-of-river, conduits, canals, low-head turbines, or hydrokinetic turbine technologies), which undermines its flexibility. There is an option to adjust "green incentives", but the turbine types (Pelton, Kaplan, Francis, or what is labeled "low-head" and we assume to be Cross-Flow) and allowable "soft" costs (such as permitting and licensing fees) options appear fixed. In contrast, the ORNL HEEA model includes a sensitivity analysis on different potential turbine technologies, as turbines are a major factor influencing electromechanical equipment costs (see section 2.2.3.) [13]. The ORNL-HEEA model was used to assess the pre-feasibility development potential of existing NPDs in the Deschutes River Basin, Oregon [13], but is not specifically tailored to that application. It is difficult to say that HEEA provides significant improvements over the USBR model; the HEEA model was never actually publicly released, and ORNL has since shifted its modeling strategy to other software (personal communication, 2017).

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[10] RETScreen Expert is available from the following website (viewer mode is free): http://www.nrcan.gc.ca/energy/software-tools/7465.

[11] Cost of the "Professional" version of RETScreen software is upwards of $800. The user is required to purchase the software to enjoy full functionality, such as saving analyses or projects.

The ORNL-IDEA model, developed to improve on HEEA, breaks down costs by individual pieces of electromechanical equipment, water conveyance equipment or structures, civil works structures, operations and maintenance (including periodic equipment replacement), access and transmission, 'soft' costs of design engineering and construction, insurance, permitting, and environmental mitigation studies [138]. The IDEA model also has a cost optimization routine based on economic cash flow parameters (e.g. installed cost, O&M cost, contingency, revenues) and site characteristics (e.g. head, flow, expected turbine selection), as well as a design optimization based solely on site characteristics [138]. The IDEA model is arguably the most state-of-the-art bottom-up SHP cost assessment model [138] and is well-suited for our purposes in terms of modeling SHP costs in the Northeast. However, the IDEA model is still in development (personal communication, 2017) and has not yet been released for public use.

We feel strongly about research being made transparent and publicly available, so an Excel-based (ubiquitous software) tool or a program that runs on R or another free and open-access software is preferred over software that requires purchase for full functionality. While the ORNL-IDEA model appears to meet many of these needs, it has not been made available to the public. We call instead for a cash flow analysis, to perform project cost and performance assessment in a bottom-up way and assess at finer scale the costs and benefits of SHP investment. A thorough cash flow model would include site-specific decision alternatives, such as fish passage improvements and hydropower capacity expansion, estimation of project costs at powered dams and NPD sites, and sensitivity analysis of uncertain project parameters (i.e., various electricity pricing, discount rate, and incentive schemes) using Monte Carlo simulation. Future work will build on this review of the literature to develop a thorough cash flow model for SHP project cost and performance assessment (Ch. 3).

3.0. BENEFIT-COST CASH FLOW ASSESSMENT OF SMALL-TO-MEDIUM-SCALE HYDROPOWER DAMS

Abstract

Although hydropower is a mature renewable energy technology, there is a paucity of comprehensive cost data for hydropower projects, particularly for small-scale hydropower (SHP) dams licensed by the Federal Energy Regulatory Commission. I use a benefit-cost cash flow model and data from 8 FERC-licensed hydropower dams in Maine coming up for relicensing in the next 10 years to estimate annuitized project costs, levelized cost of energy, and carbon emissions reductions for business as usual (keep and maintain) and hypothetical scenarios for each dam (e.g. improve hydropower generation). Annuitized costs for projects at powered dams range from \$7/kW-yr to \$58/kW-yr for removing the dam, \$44/kW-yr - \$131/kW-yr for keeping and maintaining the dam, \$56/kW-yr - \$167/kW-yr for improving hydropower generation, \$122/kW-yr - \$357/kW-yr for improving fish passage, and (the most expensive option, on average) \$136/kW-yr - \$299/kW-yr for improving hydropower generation *and* fish passage. Carbon emission reductions range from 5.1 – 36.6 tonnes/year for keep and maintain and from 8.7 -36.8 tonnes/year for improving hydropower generation. NPV analysis shows that projects other than improving fish passage and removing the dam are economically feasible (NPV>0, BCR>1) for seven of eight dams when considered individually. Sensitivity analysis shows that NPV is most sensitive to changes in the discount rate and wholesale electricity price.

Keywords: hydropower, cash flow model, benefit-cost analysis, project cost estimation

3.1. Introduction

Small-scale hydropower (SHP, plants with a nameplate capacity of 10 MW or less, see Ch. 2) is often touted as more environmentally sustainable than large hydro projects, but this assessment has recently come under fire for being spurious [21]. No matter their size, dams interrupt the natural flow of rivers and streams with impoundments, creating a barrier to historical sea-run fish passage (see [18], [19], [28]). Even small impoundments disrupt landscapes by submerging surrounding habitats (riparian buffers, forests, flood plains) under the surface of the reservoir, causing ecological changes [21], [26], [85], [111]. Run-of-river (ROR) project schemes (that divert water from the stream to turn a turbine and generate electricity), which are designed to minimally interrupt local flows as compared to reservoir-based store-and-release (SAR) project schemes, still disturb riverine environments by dewatering streams and breaking up river habitats, particularly where project schemes 'cascade' downstream [21]. Just like their large-scale counterparts, SHP operations degrade water quality, returning water to the river through the tailrace with lower dissolved oxygen content than the water upstream [85]. SHP may also interfere or detract from recreational fishing, landscape aesthetics, or property values [78].

Despite these clear limitations, we consider hydropower's technological sustainability to be comparatively strong. Like other renewable energy technologies, hydropower's biggest benefit is availability; hydroelectric turbines/generators can generate electricity anywhere there is flowing water, from rivers and streams to canals and conduits. In addition to providing baseload, intermediate, and peaking electricity to the grid, hydropower provides other grid-support services as well: 'black start' and load-following generation characteristics are of particular value [1]. Because of these services, hydropower continues to play an important role in the U.S. energy mix. And, though flows vary seasonally, hydropower is not limited by the same intermittency as solar or wind. Kosnik writes, "There is not a single state in the country that does not have the ability to benefit at least somewhat from additional small scale hydropower development" (p.5513) [14].

The Northeast region has the largest number of existing hydropower plants in any U.S. region (>600), most with capacities of 1 MW or less [1], but there is still room to grow (see Kao et al. [8] and Hadjerioua et al. [9]). Capital expenditures for hydropower projects remain steep [9], [10], [12], despite a push within turbine equipment design and manufacturing industries toward modular equipment to reduce overall project costs [6]. And, although the U.S. continues to make allowances for SHP projects on new non-powered dams and canal/conduit projects [106], even exempting certain projects from Federal Energy Regulatory Commission (FERC) relicensing (i.e., after the initial application, licensees are exempt from future relicensing applications and mitigation requirements) [107], there is a shift in the U.S. toward net maintenance (rather than construction) across its fleet of hydropower dams. In the Northeast especially, there appears to be no construction of new dams.

Existing small, powered dams still present an opportunity for licensees operating in areas with rapidly increasing electricity demand if electricity prices are reasonably high, to recoup capital expenditures through sales revenue and achieve positive net present value within a reasonable project lifetime. Renewable generators may qualify for Renewable Energy Credits (RECs, created on a per MWh basis, may be sold to consumers wishing to claim some percentage of green power usage) which provides an additional revenue stream for the project [136], [139], and may thus contribute to the generating asset's value. REC incentives are typically associated with state Renewable Portfolio Standards (RPS) programs, where states with RPS goals in place may have mandatory REC markets, voluntary markets, or both [136], [139]–[141]. Typically, mandatory REC market prices are higher than for voluntary markets because state law requires that a certain percentage of generation purchased be from 'green power' or renewable sources. In some states, such as Massachusetts, hydropower is required to be certified by an independent third party (e.g., the Low Impact Hydropower Institute, LIHI) who reviews impacts to recreational, environmental, and cultural resources [140]. RECs contribute to a hydropower dam's economic sustainability (i.e., a project's cost-effectiveness over time).

While power purchase agreements (PPAs, which stabilize wholesale electricity prices for generators within the contracted term) help balance uncertain electricity prices (see [37], [46] for a discussion of the sensitivity of capital cost to electricity pricing), even volatile REC prices enhance the value of an asset (especially smaller-scale projects with few megawatt-hours annual electricity generation) and may make the difference in a licensee's decision to pursue relicensing or consider other alternatives (e.g. surrender or decommission) when expensive fish passage improvements are required. Prescribed fish passage improvements from regulating federal agencies (e.g., National Oceanic and Atmospheric Administration, U.S. Fish and Wildlife Service) is not uncommon in FERC relicensing. In fact, the Endangered Species Act is commonly referred to as a regulatory 'hammer', because of the swift and definite impact it has on the licensee [20], who must comply with the requirements, typically under a limited time frame and often at a substantial cost [36]. It interests me to know the extent to which fish passage requirements and improvements to hydropower generation impact SHP cash flows, both with and without RECs.

Sharma et al. suggest that hydropower's role in the U.S. electricity mix is declining [3], so hydropower's economic sustainability is the main thrust of this paper. Decreasing U.S. electricity prices, the considerable range in hydropower's levelized cost of energy (LCOE, a measure often used to compare costs across energy technologies) [19], as well as high upfront capital expenditures, required even for business-as-usual operation (due to expensive licensing requirements, which can cost tens of thousands of dollars, see [142]) brings into question the economic feasibility of investment spending on hydropower [12], especially where fish passage improvements are required.

3.1.1. Maine Hydropower Dams

Maine boasts 30% of its net electricity generation from conventional hydropower [143]. This amounts to 290 MWh annually, equivalent to 1.3% of the U.S. share from utility-scale hydropower net electricity generation [143]. Though it is unlikely that Maine will see additional dam construction soon, there are some existing *non-powered* dams with a total projected 70.3 MW potential for retrofit, 21.2 MW of which is considered 'significant', i.e., possible given site characteristics and regulatory requirements, and existing *powered* dams with a projected total 122.3 MW potential for capacity expansion, 34.5 MW of which is considered 'significant' [107]. Maine's 93 FERC-licensed and FERC-exempt hydropower dams are mostly (~78%) <10 MW (SHP), with the remainder (~22%) 10 – 85 MW (data from [144]). Only 3 of the dams between 10 – 85 MW are >50 MW. Most of Maine's hydropower dams are licensed actively (or exempted) to private owners [144], regulated by FERC[12], and with a mean age of 104 years, are amongst some of the oldest dams in the country [24]. Despite its age, Maine's hydropower fleet promises to play an ongoing role in the state's energy mix under the state's updated Renewable Portfolio Standards (RPS), signed into law in 2019 [145]. The new RPS promises carbon neutrality by 2030 and 50% generation from renewables by 2050.

This study focuses on eight Maine FERC-licensed hydropower dams coming up for relicensing in the next 10 years in the Penobscot River (Table 10). Seven of eight dams are located in Penobscot County, except for Ripogenus Dam, which is in Piscataquis county. All dams except Millinocket Lake are in the West Branch of the Penobscot River. Millinocket Lake is in Millinocket Stream, a tributary of the West Branch, and is also the only non-powered dam (NPD) in the set of eight. The dams range from small (<10 MW) to medium in size (10 – 50 MW) and operate as either ROR or SAR (Table 10). The larger dams (power capacity ≥10 MW, e.g. Dolby) that operate as ROR are not diversion schemes; rather, they allow some spillover (over the top of the dam or through spillways) in addition to the water passing through the turbines to keep downstream flows equal to upstream flows. Twenty dams in Maine are certified or pending certification by LIHI as 'low impact' in terms of environmental, cultural, and historical indicators [146]. Three of these dams are within our selected eight: Medway Dam, Millinocket/Quakish Development, and Dolby Development. It is also important to note that five (Dolby, East Millinocket, Millinocket/Quakish, Millinocket Lake, and North Twin) of the eight dams are all part of the same Penobscot Mills Project operating license and work in tandem with one another, and with Ripogenus Dam (located upstream), although Ripogenus Dam is on a different operating license [128].

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[12] FERC is the regulatory body that ensures licensees are adhering to federal regulations such as the Endangered Species Act and National Environmental Policy Act (see https://www.ferc.gov/industries/hydropower/gen-info.asp).

Table 10. Summary of study dams.

Dam	FERC License No.	Power Capacity (MW)	FERC License Expiration	LIHI-certified?	Operation
Dolby	2458	20.9	9/30/2026	P	ROR
East Millinocket	2458	6.9	9/30/2026	N	ROR
Medway	2666	3.4	3/31/2029	Y	ROR
Millinocket/Quakish	2458	36.0	9/30/2026	P	ROR
Millinocket Lake	2458	0	9/30/2026	N	SAR
North Twin	2458	7.0	9/30/2026	N	SAR
Ripogenus	2571	37.5	9/30/2026	N	SAR
West Enfield	2600	13.0	5/31/2024	N	ROR

Abbreviations: P = Pending, Y = Yes, N = No; ROR = run-of-river; SAR= store-and-release

Benefit-cost analysis is a form of decision support upon which many federal agencies (including FERC) rely in their assessment of "best" project options (i.e., decision alternatives), which may include changes to hydropower generation (typically requested by the dam owner), business-as-usual, and changes to fish passage (typically prescribed by FWS or NOAA-NMFS). I consider five decision alternatives (project options, described in detail in Appendix F) in my analysis: 1) 'Keep and Maintain' the dam as-is, 2) 'Improve Hydropower Generation' (this includes power capacity expansion at the development due to additional turbines), 3) 'Improve Fish Passage' (through additional passage facilities such as fish lift or pool-and-weir), 4) 'Improve Hydro AND Fish' (a combination of the previous two decision alternatives), or 5) 'Remove Dam' (decommission and deconstruction of the dam in the waterway to allow the river to run freely through the former project site). Concerned by stakeholder comments about the lack of resources for understanding site-specific costs and benefits of small-scale hydropower production in Maine, I use a cash flow model to explore (in a transparent way) the role of the eight dams in Maine's electricity mix. I answer the following research question: *What can project cash flows tell us about the economic feasibility of potential decision alternatives for Maine's small-to-medium scale hydropower dams?*

3.2. Methods

To compare the costs and benefits of each of the five decision alternatives (Appendix F), I use a hybrid 'bottom-up' (engineering-economic) cash flow model, which I identified as the most appropriate model type for project cost and performance assessment in Chapter 2. Using a combination of regression-based and engineering-economic estimation methods, I calculate the following hydropower project cost and performance metrics for comparison: 1) capital expenditures (C_{CAP}) and annuitized project costs, 2) lifecycle carbon-dioxide (CO_2) emissions avoided, 3) capacity factor, 4) LCOE ($/MWh), 5) net present value (NPV, $/MW)[13], 6) internal rate of return (IRR), and benefit-cost ratio (BCR). Annuitized project costs (yearly project costs estimated using a discount rate to take into account the time cost of the investment over the project's lifetime) and lifecycle CO_2 emissions avoided (emissions that would otherwise come from fossil fuel generation if not produced through renewable generation) are inputs to the multi-criteria described in Ch. 5. I quantitatively assess the sensitivity of NPV to changes in the following inputs: 1) electricity price, 2) discount rate, and 3) REC price using Monte Carlo simulation. Finally, I compare the annual electricity generation at each dam under different possible decision alternatives (another model input for Ch. 5) to the total electricity generation for the State of Maine.

3.2.1. Data Overview

Data were exclusively compiled from publicly available sources (Table 11). Hydropower project license issuances are publicly available in FERC's e-library[14] [128]. For projects with multiple dam developments, I systematically reviewed FERC license issuance PDF documents for development-specific nameplate capacity information, compiling information on operations (ROR or SAR) and average annual electricity generation data. I use LIHI data [146], [147] only for the three pending/certified dams (for a full list, see Appendix G). Finally, Energy Information Administration (EIA) 2017 data [148] on annual

[13] Refer to Ch. 2 for definitions and discussion of the importance of these metrics: LCOE, capacity factor, NPV.
[14] FERC makes their library of license and other related documents publicly accessible: https://www.ferc.gov/docs-filing/elibrary.asp

electricity generation for hydropower and fuel sources for the State of Maine (e.g., petroleum, natural gas, coal, and municipal solid waste) were used to calculate lifecycle CO_2 emissions avoided.

Table 11. Data type by source

Data Source	No. Maine Dams	Power Capacity (kW)	Annual Electricity Generation (MWh)	C_{CAP} ($)	Annual Revenue ($/yr)
FERC Licenses[a] [128]	64	Y	Y	Y*	N
FERC Relicense Tracking Data [144]	95	Y	N	N	N
Annual Electricity Generation Reports[a] [128]	39	Y	Y	N	N
2015 Maine Hydropower Study [107]	149	N	N	Y	Y
LIHI Data[a] [146], [147]	20	Y	N	N	N
FERC-issued Environmental Assessment [128]	10	Y	Y	Y*	Y*
EIA [148]	46	Y	Y	N	N

[a]Values submitted by the licensee and are accessible within the license docket on the FERC eLibrary.
*In many cases, values are either not reported or are reported in aggregate for a project with multiple developments, or multiple project holdings.

3.2.2. Project Performance: Annual Electricity Generation

Annual electricity generation is an important factor in understanding the economic feasibility of different decision alternatives. While the average annual electricity generation data comes from FERC licenses (Table 12), I estimate additional annual electricity generation using technically feasible power capacity estimates from the 2015 Maine Hydropower Study [107]. To do this, I first calculate the annual capacity factor using average annual electricity generation data from the FERC license for each dam site. Capacity factor (*CF*, Equation 24) is an indicator of the project's actual, licensee-reported performance as a proportion of the maximum possible performance in a given year (i.e., turbines generating at maximum rated capacity 24 hours a day, 365 days a year) (Equation 24, a duplicate of Eq. 10 in Ch. 2). Estimated additional annual electricity generation values were calculated using the 2015 Maine Hydropower Study estimates for power capacity, which identifies potential opportunities for hydropower installation or expansion on existing powered and non-powered dam infrastructure (Equation 25). I use Equation 25 to calculate additional annual electricity generation because the estimates reported in the 2015 Maine

Hydropower Study are based on an assumed flat annual capacity factor of 0.38 for each site, which is too generalized for our purposes. A flat annual capacity factor suggests that production is not only the same year over year, but also at each dam in the set of 8. I do not consider degradation of hydropower electromechanical equipment because no other U.S. studies do (e.g., [9]–[13]), and because hydropower equipment degradation is considered negligible compared to solar photovoltaic equipment [12], where studies considering replacement costs estimate replacement after 25 years or more. Equations 24 and 25 are circular, since either CF or annual electricity production (AEP, given in MW) is a required input for each, but I use them for different purposes. I use the observed AEP reported in the FERC licenses to estimate CF for all hydropower sites (except Millinocket Lake, where I maintain the CF = 38% assumption from the Maine Hydropower Study [107]), and then use the CF estimates to, in turn, estimate a more accurate AEP value for additional capacity power capacity under 'Improve Hydropower Generation' and 'Improve Hydro AND Fish' decision alternatives (additional capacity data from the Maine Hydropower Study [107]).

$$CF = \frac{AEP}{P * 24_{hrs} * 365_{days}} \quad (24)$$

where P= power capacity (MW); P = installed power capacity (MW); AEP is observed.

$$AEP = P * 24_{hrs} * 365_{days} * CF \quad (25)$$

Table 12. Capacity factor and additional power capacity inputs used to estimate additional annual electricity generation

Dam Name	Total Annual Capacity Factor † (%)	Additional Power Capacity (MW) [107]	Estimated Additional Annual Electricity Generation (MWh/year)*
Dolby	54	0.00	0
East Millinocket	62	4.06	22,090
Medway	93	2.46	20,108
Millinocket/Quakish	64	0.00	0
Millinocket Lake	38	0.22	732
North Twin	77	4.03	27,327
Ripogenus	71	7.47	46,576
West Enfield	64	0.00	0

* = Estimated using additional power capacity from the 2015 Maine Hydropower Study (column 3, [107]) and total annual capacity factor; †= calculated using average annual electricity generation reported in FERC licenses [128].

3.2.3. CCAP, O&M, and Annuitized Project Costs

Estimates for C_{CAP} were calculated for dataset completeness. While the 2015 Maine Hydropower Study includes estimates for C_{CAP} for some dam sites, it is unclear whether the values are calculated based on NSD construction or NPD construction. For C_{CAP}, I first calculate initial costs (*ICC*) using the Hall et al. [149] method and escalate to USD 2019 (Equation 26). ICC is calculated differently depending on the decision alternative because construction needs are different (Table 13); e.g., ICC for 'Keep and Maintain' only factors in the cost of licensing because we assume no construction outside of regular maintenance). When estimating ICC *for* 'Improve Fish Passage' and 'Improve Hydro AND Fish' decision alternatives at Millinocket Lake Dam, I assume the power capacity is equal to the additional power capacity for the sake of producing an estimate because keeping and maintaining the dam is non-powered (and assuming P=0 would result in a cost of $0 for improvements to fish passage construction). ICC for dam removal is treated somewhat differently than the non-removal alternatives (Eq. 26). Equation 27 comes from Blachly and Uchida [150], who use dam height and length parameters (Table 14) and coefficients determined through linear regression to estimate the cost of removal for the 8 dams concerned.

$$ICC = \left(a * P^b\right) * i \tag{26}$$

where P = current (i.e., existing) power capacity (MW); i = cost escalation factor (interest rate calculated using the consumer price index, CPI); a and b are coefficients borrowed from Hall et al. [36].

$$ICC_{remove} = (30{,}557h + 1375l) * i \tag{27}$$

where h = dam height (ft); l = length of dam (ft).

Table 13. Coefficients for ICC estimation for non-removal decision alternatives using Eq. 26.

Cost Category	*a*	*P*	*b*
Licensing*	210000	existing	0.7
Hydro Construction	1400000	additional	0.81
Fish Passage Construction	2066388	existing	0.96
Decision Alternative	**Cost Equation Components**		
Keep and Maintain	Licensing		
Improve Hydropower Generation	Hydro Construction + Licensing		
Improve Fish Passage	Fish Passage Construction + Licensing		
Improve Hydro AND Fish	Hydro Construction+ Fish Passage Construction + Licensing		

* = in NPD cases, the licensing coefficient *a* is replaced with 310000; *P*= power capacity (MW); *a* and *b* are coefficients estimated by Hall et al. [36].

Table 14. Inputs for estimating ICC for dam removal using Eq. 27.

Dam Name	Length (ft)	Height (ft)
Dolby Dam	1390	56
East Millinocket Dam	700	31
Medway Dam	541	35
Millinocket/Quakish	1110	30
Millinocket Lake Dam	198	14
North Twin Dam	972	35
Ripogenus Dam	940	225
West Enfield Dam	970	23

The main difference between C_{CAP} and ICC is that the former considers the contingent costs related to construction, whereas the latter is just inclusive of equipment and licensing (i.e., investment) costs. In this case, we calculate contingency as a percentage of ICC, adding it back on top of ICC to calculate C_{CAP}. We use the total percentage suggested by USBR (35%), which encompasses both construction contingency costs (20%) and uncertainties relating to project engineering and management costs (15%) [10]. We apply the 35 percent contingency value to the entire ICC value because there are significant uncertainties related to licensing costs, often concerning administrative fees and studies performed by regulatory agencies (e.g., USFWS) on behalf of the licensee, which they are required to reimburse [142], [151]. C_{CAP} for dam removal is equal to the ICC value for removal because when the dam is kept and maintained as is, there are no construction costs or construction engineering/management to consider as with other decision alternatives.

All project costs (capital expenditures and O&M) were then annuitized using a discount rate (d) of 6.2 percent and a financial lifetime (T) of 20 years [152] (Equation 29).

$$C_{CAP} = (ICC * n) + ICC \quad (28)$$

where C_{CAP} *= capital expenditures; n = contingency (35 %).*

$$C_{ann} = C_{CAP} * \left(\frac{d(1+d)^T}{(1+d)^T - 1}\right) + O\&M \quad (29)$$

where C_{ann}*= annuitized costs; d = discount rate; T = financial lifetime; O&M = O&M cost.*

Annual O&M was calculated following O'Connor et al.'s regression-based method [11], with some modifications based on the set of decision alternatives. For 'Keep and Maintain' and 'Improve Fish Passage' (with no hydropower improvements), I use the existing power capacity (P), while for decision alternatives that include improving hydropower generation, I use the total power capacity (P, which includes both existing and additional power capacity) (Equation 30). I set O&M equal to zero for 'Remove'. For the non-powered dam, to estimate a non-zero dollar amount for the 'Keep and Maintain' and 'Improve Fish Passage' decision alternatives, I assume that the dam's power capacity is equal to the estimated additional capacity value from the Maine Hydropower Study [107]. This assumption means that all decision alternatives for Millinocket Lake Dam (the NPD) have the same O&M cost. Annuitized project costs (C_{ann}, Equation 29) include annual O&M and C_{CAP}, to represent the yearly cost to the licensee for the financial lifetime of the project. For the 'Keep and Maintain' decision alternative, annuitized project cost is simply equal to O&M because there are no capital expenditures.

$$O\&M = 225417P^{0.547} * i \quad (30)$$

3.2.4. Annual CO_2 Emissions Avoided and Greenhouse Gas (GHG) Benefits

Life cycle CO_2 emissions avoided represent the social benefits in a renewable energy asset's NPV. Energy projects emit CO_2 throughout their lifetimes, from extraction to decommission and end-of-life deconstruction [153]; including land, fuel, and consumptive water use [61]). While hydroelectric generation does not emit CO_2 in operation, hydropower still suffers from life cycle GHG emissions from construction: raw material extraction, transportation, and the actual building of the dam [153]. The key takeaway is that hydropower emits less than non-renewable sources and contributes to Maine's RPS goals. I estimate annual CO_2 emissions reductions based on Maine's current electricity generation mix, classifying the site-specific lifecycle emissions factors as ROR or SAR (classified as reservoir-based hydropower by Song et al.) based on dam design and operation [153]. Different hydropower project types (e.g., ROR and SAR) have different lifecycle emissions because of their different constructions: SAR dams may be taller or have additional spillways to accommodate changes in reservoir volume under storm conditions [1], whereas ROR dams may be diversions from the main stream or allow water to flow over the top [1], [21], [100]. These design differences mean that not only will the quantity of material needed for construction vary across these two designs, but also the methane releases from submerged vegetation will be different (e.g., higher for SAR dams, and also variable by latitudinally-defined vegetation zones) [153]. For SAR dams, annual CO_2 emissions reductions will be lower than for ROR dams because the lifecycle emissions are higher for that type of design.

I estimate annual fuel emissions reduction (*GHG*, in tonnes) using EIA form 923 data from 2017 (which details annual electricity generation (MWh) by fuel type, power plant, and state [148]) by estimating the life cycle carbon emissions avoided (GHG_{hydro}, tonnes CO_2/MWh) based on avoiding Maine's electricity generation mix using hydropower and multiplying this value by the average annual electricity production (*AEP*, Equation 31). To estimate GHG_{hydro} (Equation 32), which will have different results different for SAR and ROR life cycle emissions avoided ([153]), I use the fraction of electricity generated from fuels (petroleum, coal, gas, and municipal solid waste) in Maine (f_{fuel}, calculated from EIA Form 923 [148], assuming life cycle emissions for gas ([61]) and point-source emissions factors for petroleum, coal, and municipal solid waste ([148]), Table 15). This fraction of electricity generation from fuel sources (f_{fuel}, Equation 33) is multiplied by the difference of the life cycle emissions factor for hydropower (minus construction, different for SAR and ROR [153]) and the total emissions factor for Maine's electricity generation mix (gCO_2/kWh).

$$GHG = GHG_{hydro} * AEP \quad (31)$$

where GHG =annual emissions reduction (tonnes); GHG_{hydro} = life cycle CO_2 emissions avoided (tonnes CO_2/MWh) through hydropower generation; AEP = annual electricity generation (MWh).

$$GHG_{hydro} = (EM_{Total} - EM_{hydro}) * f_{fuel} \quad (32)$$

where EM_{Total} = total emissions factor, Maine electricity generation from fuel (tonnesCO_2/MWh); EM_{hydro} = life cycle emissions factor, hydropower (tonnesCO_2/MWh); f_{fuel} = fraction of electricity generated from fuels in Maine (%).

$$f_{fuel} = f_{pet} + f_{gas} + f_{coal} + f_{MSW} \quad (33)$$

f_{pet} = weighted emissions factor, petroleum (tonnesCO_2/MWh); f_{gas} = weighted emissions factor, natural gas (tonnesCO_2/MWh); f_{coal} = weighted emissions factor, coal (tonnesCO_2/MWh); f_{MSW} = weighted emissions factor, municipal solid waste (tonnesCO_2/MWh).

I also calculate monetized annual social benefits from emissions reductions (NPB_{soc}) (Equation 36). RECs and carbon pricing are alternative revenue streams, outside of project revenues from electricity sales, that monetize the social benefits garnered from renewable electricity projects (Equation 34 – 35). RECs are earned from hydropower production (based on MWh of electricity generated) and are often ignored in the assessment of project finances, possibly because the prices can be highly volatile [154]. However, New England states operate within a REC compliance market (i.e., RPS goals require states to produce a certain minimum amount of renewable energy) [140], [155], so it makes sense to consider RECs because certificate sales bring real returns to SHP projects. Carbon price is a measure used by the EPA and other agencies to estimate the monetized value of impacts from GHG emissions (or benefits from GHG emissions avoided) [156]. The idea behind carbon pricing is that it captures the social climate-related externalities not accounted for in markets related to the sale of energy [156], [157]. While carbon pricing is considered a climate best practice, U.S. carbon markets do not exist at scale outside of California; as of now, a carbon price is not something that contributes to project revenues [139], [156], [157].

$$NPB_{REC} = P_{REC} * AEP * i \tag{34}$$

where P_{REC} *= price of REC in 2018 ($)* [139]; *i = interest rate*

$$NPB_{CO2} = P_{CO2} * EM \tag{35}$$

where P_{CO2} *= estimated price of carbon in 2020 ($)* [156]

$$NPB_{soc} = NPB_{REC} + NPB_{CO2} \tag{36}$$

Table 15. GHG emissions produced from the generation mix in Maine

Electricity Source	**Annual Gen. (GWh)** [148]	**Annual CO_2 Emissions from Combustion (tonnes)** [148]	**% Gen. by Type** [148]	**%Total Gen.** [148]	**Life Cycle Emissions Factor (gCO_2/kWh)**	**Point Source Emissions Factor (gCO_2/kWh)**	**Emissions Factor to Use (gCO_2/kWh)‡**	**Weighted Emissions Factor †**
PET	117	134,006	5			1,147	1,147	58
GAS	1,915	742,423	83		449 [61]	388	449	373
COAL	58	158,967	3		1,000 [61]	2,726	2,726	69
MSW	217	407,936	9			1,876	1,876	177
Total Fossil Fuels	2,308	1,443,332	100	27		625		676
ROR Hydro	3,025*	0*	33*		10 [153]		180	
SAR Hydro					190 [153]		131	
Other Renewables	3,849	0	67					
Total Renewable	6,874	0	100	73				

*= No way to differentiate diversion and reservoir hydropower, here; ‡ = emissions factor to use in weighting (refers to the fact that point source emissions factors are used for petroleum, coal, and municipal solid waste, while the life cycle emissions factor is used for gas); † = calculated based on column 7, used in the estimation of GHG emissions from fuel sources avoided through hydropower generation.

3.2.5. Project performance indicators: LCOE, NPV, IRR, and BCR

As discussed in Ch. 2, LCOE (Equation 37) is an indicator of a project's costs per unit of electricity generated. It is a useful way to compare the cost-effectiveness of different generation technologies. Eq. 37 duplicates Eq. 11 and Eq. 38 duplicates Eq. 12 from Ch. 2, excluding state and federal tax for simplicity. I do not consider federal or state taxes to temper the impact of the respective incentive programs in the calculation of LCOE (e.g., Zhang et al. [12]) because the program most relevant to small-to-medium scale hydropower in Maine is the RECs related to updated RPS goals. The effect of state or federal taxes would simply be to increase costs (and LCOE) proportionately at each hydropower site. NPV is an indicator of the value of future revenues (i.e., for the project's lifetime) at present. NPV takes into account both the discounted costs (including C_{CAP} and O&M) and benefits (revenues, monetized annual CO_2 emissions reductions benefits) of electricity generation, including inflation and equipment degradation over time, to give a sense of the potential long-term value of the project to the owner. I calculate NPV as the cumulative net present benefits less the cumulative net present costs. Net present benefits (*NPB*) are calculated using Equation 40. Annual revenue (*R*) is calculated using the wholesale electricity price (escalated using -0.65% [158], a value calculated using the average projected prices from all sectors (residential, commercial, industrial)) and annual electricity generation. Where decision alternatives include improvements to hydropower, additional annual revenue due to additional generation is calculated using additional capacity estimates from the 2015 Maine Hydropower Study [107] (and corresponding additional annual electricity generation estimates).

$$LCOE = \frac{L(\mathrm{C_{CAP}}) + O\&M}{AEP} \qquad (37)$$

where L = fixed charge rate (applied to C_{CAP} *to represent the annual costs of* C_{CAP} *(\$/yr)); O&M = annual O&M cost (\$/yr);*

$$L = d + \frac{d}{(1+d)^T - 1} \qquad (38)$$

where d = discount rate; T = project financial lifetime.

$R = (P_e * r_{esc}) * AEP$ (39)

where R = revenue (\$/year); P_e = electricity price (\$); r_{esc} = electricity price escalation rate (%)

$$NPB = \sum_{i=1}^{T} \frac{R}{(1+d)^t} \quad (40)$$

$$NPV = C_o + \sum_{i=1}^{T} \frac{R-c_i}{(1+d)^t} \quad (41)$$

where C_o = initial investment cost; c_i = sum of annual costs for year t.

Total social benefits (Equation 36) are defined as positive externalities [159], or additional to net benefits to society from renewable generation, because GHG emissions (a negative externality associated with electricity generation from carbon-emitting technologies) are avoided in hydropower generation. In my assessment, social benefits are represented by GHG benefits not captured in the financial assessment of the generating asset); they are calculated as the sum of (a) annual benefit from REC sales (based on annual electricity generation, Eq. 34), and (b) annual benefit from carbon pricing (based on annual GHG emissions avoided, Eq. 35). I consider RECs and carbon pricing in a separate NPV_{soc} calculation because of the historical volatility of REC prices and the general disagreement about the social cost of carbon (i.e., carbon pricing). Anecdotally, RECs contribute to a licensee's assessment of project value but are considered secondary or additional benefits due to the volatile nature of pricing, and thus do not contribute to the primary assessment of project value. Besides, there is currently no global market for carbon pricing yet, but there could be in the future.

$$NPV_{soc} = NPB_{soc} + NPV \quad (42)$$

IRR and BCR are additional helpful indicators of project performance. IRR is typically calculated with NPV because it is an indication of the discount rate at which the NPV is equal to zero and thus adds specificity to NPV. While NPV indicates whether a project will gain sufficient revenues in its lifetime to offset the costs of investment, IRR indicates how likely it may be that a project will be lucrative; the higher the IRR is in relation to the discount rate, the more certain an investor may feel that the investment is a good one. IRR is calculated by setting NPV (Eq. 41) equal to 0 and solving for discount rate (*d*). BCR (Equation 43, duplicating Eq. 9 from Ch. 2) is often used to assess the cost-effectiveness for potential hydropower development (e.g., [13], [53], [116]). BCR values greater than 1 indicate that a project is cost-effective. BCR values equal to 1 are the same as an NPV equal to 0, indicating a break-even project. BCR values less than 1 are typically not considered cost-effective (the exception by USBR [124], which uses BCR >0.75 as discussed in Ch. 2) and are thus deemed infeasible. Though BCR values less than or equal to 1 are indicative of negative project lifetime cash flows, it is ultimately up to the licensee to decide how to proceed with relicensing.

$$BCR = \frac{\sum_{t=1}^{T} \frac{Benefits}{(1+d)^T}}{\sum_{t=1}^{T} \frac{Costs}{(1+d)^T}} \tag{43}$$

where T = financial lifetime (years); t = year; d = discount rate (%).

3.2.6. Uncertain Inputs: Electricity Price, Discount Rate, REC, Carbon Price

I perform an analysis of NPV, IRR, and BCR first using static values for uncertain inputs, then considering possible variation in a sensitivity analysis. Electricity price is variable, so I used the locational marginal price (LMP, i.e., wholesale electricity price) 5-year average ($35.15/MWh) for my static input analysis of NPV (Table 16). I use a discount rate (6.2 percent) identified by O'Connor et al. [11] as the 'most likely' rate (i.e., appropriate) for small-scale hydropower baseline cost estimation. The minimum discount rate (3%) is more commonly used by the U.S. government to assess the viability of long-term investments [159]. The maximum discount rate, 12 percent, is the value reportedly used by the licensee (according to recent NEPA documents for similar (recently relicensed) sites [128]). Finally, I used a mandatory market REC value of $30/MWh [136], [139], which sits comfortably within the range of values for New England states' respective mandatory markets ($0 - $60/MWh [136]) as the 'most likely' REC value. Based on these New England REC market values, I use $1/MWh as the lower bound (because $0/MWh would be equivalent to no REC price, which is effectively the same as my calculation of the financial NPV estimates) and $60/MWh for the upper bound. I do not consider revenues from voluntary market RECs because they are nominal by comparison. Finally, I use a 'most likely' carbon price of $42/tonne (the EPA-projected 2020 value (estimated with 3% discount rate) used to estimate social impact), a recent California Air Resources Board-published auction price of $17.87/tonne ([160]) for the lower bound and \$110/tonne (a value proposed by the National Research Council in the *Hidden Cost of Energy* report [157]) as an upper bound for sensitivity analysis. While there are existing international carbon markets, I wanted to focus on the U.S. context (which by and large does not have existing carbon markets, so I use values published by U.S. sources for this purpose.

Table 16. Wholesale electricity price. Source: ISO New England Pricing Reports *[161]*.

Year	LMP Average (\$/MWh)	Std. Dev. (\$/MWh)
2015	40.81	16.15
2016	29.07	7.62
2017	32.50	10.67
2018	42.63	15.59
2019	30.76	8.49
Average	**35.15**	**11.70**

Because wholesale electricity price, discount rate, and REC value are uncertain inputs, I performed a sensitivity analysis using Monte Carlo simulation in @Risk software. Monte Carlo simulation generates thousands of iterations of the output using different combinations of inputs to determine the probability of certain model outcomes. Monte Carlo simulation effectively tests the sensitivity of the model output (here, NPV) to key inputs (discount rate, electricity price, REC price) and determines the probabilistic distribution of possible outputs. I use 2,000 simulations and identify the range of input parameters (e.g., min, most likely, max) for the distribution of uncertain inputs (Table 17). I assume triangular distributions for all uncertain inputs, where simulations may be based on limited sample data and decisions must be made on best available knowledge (which is why we make use of the "most likely" value in estimation).

Table 17. Sensitivity analysis input parameters.

Input	Units	Max	Most Likely	Min
REC Price [136]	\$/MWh	60	30	1
Carbon Price	\$/tonnne GHG avoided	110 [157]	42 [156]	18 [160]
Discount rate	%	12.0 [128]	6.2 [11]	3.0[159]
Electricity Price	\$/MWh	60	35 [161]	20

Triangular distributions are assumed for each input parameter.

3.3. Results

Overall, improvements to hydropower generation or (where no additional power capacity is technically feasible) keeping and maintaining the dam as-is are the most economically feasible of the five decision alternatives, with seven of eight dams achieving positive NPVs over the 20-year lifetime. For all 5 decision alternatives at the 7 powered dams, NPV estimates using static values for uncertain inputs (discount rate, electricity price) range from $-11.2 million to $67.8 million (both the minimum and the maximum estimates are from Ripogenus Dam), with a mean NPV of $23.5 million across all powered dams and decision alternatives. When looking on a 2019 USD/kW basis, the results are slightly different because the dams range so much in size. NPV estimates range from $-1,102/kW (Medway Dam, 'Improve Fish Passage') to $1,713/kW (Ripogenus Dam, 'Keep and Maintain'), with a mean value of $334/kW across all powered dams and decision alternatives. IRR ranges from -2 percent (East Millinocket, 'Improve Fish Passage') to 130 percent (Ripogenus, 'Keep and Maintain'), and financial BCR ranges from 0.0 (all 7 powered dams, 'Remove') to 2.9 (Ripogenus, 'Keep and Maintain') across all decision alternatives at powered dams.

'Keep and Maintain' ($-1.3 million to $64.3 million, or $-6,038/kW - $1,713/kW) and 'Improve Hydropower Generation' ($-2.3 million - $ 67.8 million, or $-5,144/kW - $1,506/kW) performed the best for all (powered and NPD) dams. Removal is considered economically unfeasible at all dams if the licensee must bear the cost alone and removal is not compensated by improved hydropower generation at another licensee-owned dam. Two (Ripogenus and Millinocket/Quakish) of the 7 powered dams achieve positive NPV values for all decision alternatives except removal. The exceptions to these general themes are the decision alternatives at Millinocket Lake, which are *all* economically unfeasible (NPV<0) because none of them generate enough revenue to offset the initial capital expenditure.

3.3.1. Project Costs: Annuitized Costs, LCOE

Annuitized project costs range from $8/kW - $575/kW across all 7 powered dams and 5 decision alternatives and have a mean value of $160/kW (Table 18). 'Keep and Maintain' is the second-lowest-cost decision alternative, because costs amount to the bare minimum need to relicense the dam and keep it structurally sound. Unsurprisingly, ‘Improve Fish Passage’ and ‘Improve Hydro AND Fish Passage’ have some of the highest estimated annual costs, because improvements to fish passage alone do not achieve market returns. Again, it is important to note that fish passage improvements may be required by the licensee according to various legal statutes. Again the NPD outlier, Millinocket Lake has annuitized project costs ranging from $1,129/kW - $278 thousand, depending on the decision alternative. Removal is, across the board, the least expensive (annuitized costs range from $8/kW to $64/kW, with a cost of $277,668 for Millinocket Lake, the NPD), but lowest valued decision alternative because dam removal comes with no future revenue stream to offset negative cash flows.

Table 18. Annuitized project costs (2019 USD/kW-yr) for decision alternatives at selected dams.

Dam Name	**Keep Maintain**	**Improve Hydro**	**Improve Fish Passage**	**Improve Hydro AND Fish**	**Remove**
Dolby Dam	$58	$72	$170	$174	$21
East Millinocket Dam	$95	$255	$274	$419	$34
Medway Dam	$131	$352	$372	$575	$64
Millinocket/Quakish	$45	$57	$134	$138	$8
Millinocket Lake Dam*	N/A	$1,129	N/A	$1,952	N/A
North Twin Dam	$95	$253	$273	$417	$42
Ripogenus Dam	$44	$94	$132	$173	$27
West Enfield Dam	$72	$88	$209	$213	$19
Mean Project Cost	**$73**	**$288**	**$223**	**$508**	**$31**

N/A = Not applicable because Millinocket Lake Dam is currently non-powered (cannot divide by zero). The total annuitized cost for ‘Keep and Maintain’ is $100,251; $277,668 for ‘Improve Fish Passage; and $85,343 for ‘Remove’.

I calculated LCOE for all decision alternatives except dam removal because lifetime removal costs cannot be levelized across annual electricity generation (Table 19). LCOE is generally lowest for Ripogenus Dam across all decision alternatives (except ‘Improve Hydropower Generation’, where Millinocket/Quakish has a value $0.001 less), an unsurprising result given that the annual electricity generation values for Ripogenus Dam are highest and the annuitized project costs are not the highest. It follows that LCOE for Millinocket Lake Dam is highest for all 5 decision alternatives, because ‘Keep and Maintain’ and ‘Improve Fish’ are associated with 0 MWh electricity generation at the NPD, and both

‘Improve Hydropower Generation’ and ‘Improve Hydro AND Fish’ lifetime costs are levelized across only 730 MWh annually. There are a few dams with cost-competitive decision alternatives (wholesale electricity price, to which we compare LCOE, is assumed to be $0.035/kWh, or $35/MWh): ‘Keep and Maintain’ and ‘Improve Hydropower Generation’ are cost-competitive decision alternatives for 5 of 7 dams (including sites where LCOE equals electricity price), while ‘Improve Fish Passage’ and ‘Improve Hydro AND Fish’ are only cost-competitive for Millinocket/Quakish and Ripogenus. ‘Remove’ is not a competitive option at any dam site.

Table 19. LCOE (2019 USD/kWh) for selected dams and decision alternatives.

Dam Name	Keep and Maintain	Improve Hydropower Generation	Improve Fish Passage	Improve Hydro AND Fish
Dolby Dam	**0.025**	**0.028**	0.048	0.049
East Millinocket Dam	**0.035°**	0.044	0.068	0.063
Medway Dam	**0.032**	0.038	0.061	0.054
Millinocket/Quakish	**0.016**	**0.018**	**0.032**	**0.032**
Millinocket Lake Dam*	N/A	0.445	N/A	0.670
North Twin Dam	**0.028**	**0.035°**	0.054	0.050
Ripogenus Dam	**0.014**	**0.019**	**0.028**	**0.030**
West Enfield Dam	**0.026**	**0.028**	0.050	0.051

Bold text indicates LCOE is competitive with (i.e., lower than) prevailing electricity prices; N/A = Not applicable because Millinocket Lake Dam is currently non-powered (cannot divide by zero). ° = LCOE values are equal to prevailing electricity prices. The cost for ‘Keep and Maintain’ is $100,251; $277,668 for ‘Improve Fish Passage’.

3.3.2. Annual Electricity Generation, Electricity Revenues, and REC Revenues

The average annual electricity generation for the selected dams ranges from 0 – 234 GWh/year under existing power capacities (Figure 10). Where additional technically feasible capacity was identified by the 2015 Maine Hydropower Study, additional generation estimates for the selected dams range from 2 – 47 GWh/year. With improvements to hydropower generation, Medway Dam would see a 72 percent; East Millinocket Development 59 percent; North Twin Development 58 percent, and Ripogenus Dam 20 percent increase in annual electricity generation. Notably, East Millinocket and North Twin Developments are both part of the Penobscot Mills Project (FERC No. 2458). Ripogenus Dam is owned by the same licensee, and although it is regulated under a different license (FERC No. 2571), it is operated in tandem with the

Penobscot Mills Project dams. Despite the high cost of adding turbine units or upgrading to more efficient turbines, market returns from additional electricity generation typically make up for high up-front capital costs. And, because equipment degradation is assumed to be negligible for SHP [12], annual electricity generation is constant across all 20 years of the project lifetime. At Millinocket Lake, the additional technically feasible power capacity is so low (220 kW, generation 732 MWh/year) that the revenues from electricity sales ($26,742/year) for decision alternatives improving hydropower generation do not make up for the high annuitized cost ($961/kW) on an NPD, as evidenced by the high LCOE in Table 19. It would not make good economic sense to retrofit the existing NPD (the only one in this limited sample of Maine dams) if it were licensed by itself or with another small hydropower dam. However, because the Millinocket Lake development is paired with four other medium-sized hydropower dams under the Penobscot Mills Project license (FERC No. 2458), it could be kept and maintained at a loss, while the Project as a whole still experiences net positive returns.

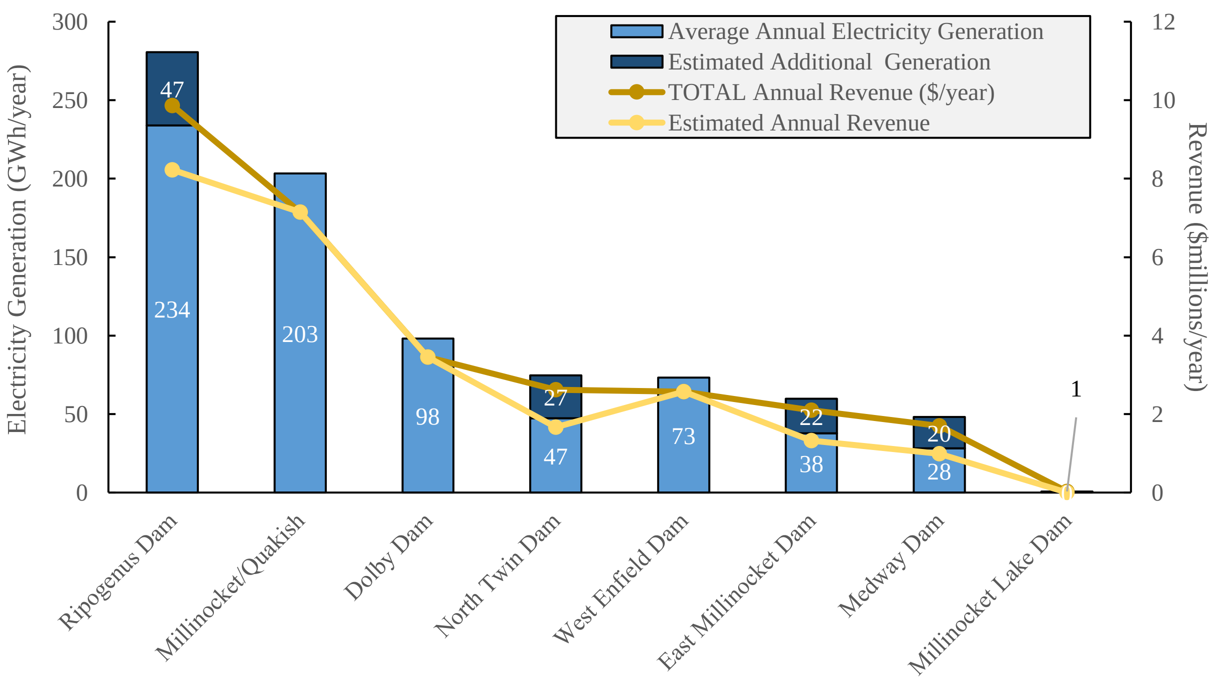

Figure 10. Reported existing annual electricity generation with estimated additional annual electricity generation (calculated using site-specific capacity factors). Estimated existing revenue (and estimated additional revenue) is also depicted for the 8 dams. 1 GWh = 1000 MWh. The line graph is not a time trend; rather, it emphasizes the relationship between generation (GWh) and revenue at a project site under non-removal decision alternatives. Data source(s): FERC licenses *[128]*, 2015 Maine Hydropower study *[107]*.

It is worth remembering that four of the hydropower dams considered here are comfortably medium-sized (10 – 50 MW). For context, each of these medium-sized dams (West Enfield, Millinocket/Quakish, Dolby, Ripogenus) contribute at least 1 percent of Maine's total electricity generation (Table 20). Overall the 8 dams contribute 6 percent of Maine's total 11,281 GWh under 'Keep and Maintain' and could contribute 7 percent under 'Improve Hydropower Generation' and 'Improve Hydro AND Fish', assuming that any additional capacity in hydropower replaces existing power capacity from other resources (i.e., no net additional capacity is added). The Penobscot Mills Project alone currently contributes 3 percent of Maine's total electricity generation, but with additional (i.e., improved) hydropower capacity, it could contribute 4 percent of the total electricity generation.

Table 20. Current and potential hydroelectric generation at sample dams as compared to Maine's total annual electricity generation.

Dam Name	**Existing Annual Electricity Generation (MWh)** [128]	**Existing % of Maine Total** [148]	**Estimated Total Annual Generation (MWh)***	**Estimated % of Maine Total**
Ripogenus	234,000	2	280,576	2
Millinocket/Quakish	203,300	2	203,300	2
Dolby	98,100	1	98,100	1
North Twin	47,300	0	74,627	1
West Enfield	73,200	1	73,200	1
East Millinocket	37,700	0	59,790	1
Medway	28,118	0	48,226	0
Millinocket Lake	0	0	732	0

* Additional power capacity data come from the Maine Hydropower Study [107], table values calculated using additional capacity and site-specific capacity factor (based on average annual electricity generation, column 1 [128]). **Note:** Maine total annual electricity generation = 11,280,700 MWh (11.3 GWh) [148].

My estimates for both annual electricity generation and electricity sales revenues (for 'Improve Hydropower Generation' and 'Improve Hydro AND Fish' decision alternatives only) are higher than estimates from the Maine Hydropower Study (Table 21). Recall, the Maine Hydropower Study uses a capacity factor of 0.38, whereas I use site-specific capacity factors ranging from 0.54 to 0.93 (Table 12), calculated based on FERC license data for average annual electricity generation. This difference almost certainly accounts for the difference in estimates. My estimates for additional annual electricity generation are at least 48 percent higher for every dam with technically feasible additional hydropower capacity except for Millinocket Lake Dam. The difference between my estimates and Maine Hydropower Study estimates for additional annual revenue range from -0.42 to 0.46 percent. Again, the Maine Hydropower Study uses a $50/MWh wholesale electricity price (the New England 10-year average value in 2015), which is $15/MWh greater than the $35/MWh average wholesale price for the last five years in Maine. The lower wholesale electricity price is counteracted by the higher, site-specific capacity factors, making most of my annual revenue estimates (except for Millinocket Lake Dam, where I use the same 0.38 capacity factor as the Maine Hydropower Study) higher as a result. I maintain that my estimates are more accurate than the Maine Hydropower Study estimates, but this comparison does highlight the need for a sensitivity analysis using electricity price (see section 3.3.4.).

Table 21. Comparison between annual electricity generation and revenue estimates.

Dam Name	Estimated Additional Generation (MWh/year)*	2015 Maine Hydropower Study Estimated Additional Annual Electricity Generation (MWh/year) [107]	Additional Generation Difference (%)	Estimated Additional Annual Revenue ($thousands/year)	2015 Maine Hydropower Study Estimated Additional Revenue ($thousands/year) [107]	Revenue Difference (%)
Dolby	0	0	0	$0	$0	0
East Millinocket	22,090	13,530	48	$776	$730	6
Medway	20,108	8,190	84	$707	$442	46
Millinocket/Quakish	0	0	0	$0	$0	0
Millinocket Lake	732	730	0	$26	$39	-42
North Twin	27,327	13,410	68	$961	$723	28
Ripogenus	46,576	24,880	61	$1,637	$1,342	20
West Enfield	0	0	0	$0	$0	0

* = Estimated using additional power capacity from the 2015 Maine Hydropower Study ([107]) and total annual capacity factor (Table 12).

If fish passage improvements are so expensive (Table 19), and project revenues are slow to recoup the costs, what prompts a licensee to make changes to fish passage if they are not prescribed by federal agencies or legally required by statute? In some cases, licensees may seek to improve fish passage to acquire LIHI certification, which signals their status as a 'green power' generator in mandatory and voluntary markets alike [141]. In Maine, which does not require certification for the mandatory REC market, LIHI certification still provides a clear identifier of up-to-date fish passage requirements, which is required for hydropower generators to participate in Maine's mandatory market. LIHI-certified facilities may recoup the cost of fish passage improvements (where relevant) through REC revenues, which can be as high as $60/MWh in mandatory markets [136], [139]. Though voluntary market RECs are valued at a small fraction of the mandatory market RECs, they still provide additional project revenue at $0.37/MWh (2016 USD escalated to 2019 USD). If REC prices are as high as $35/MWh with a carbon price of $42/tonne CO_2, I estimate that REC benefits could be as high as $8.4 million/year, CO_2 benefits at $1.5 million/year, and total GHG benefit at $10 million/year (Figure 11) for Ripogenus Dam, which has the highest annual electricity generation of the 7 powered dams. Emissions avoided (calculated as a function of foregone electricity generation from fuel sources) could be as high as 36.6 tonnes/year in our sample (Millinocket/Quakish). Worth noting is that emissions avoided for Ripogenus are not as high as for Millinocket/Quakish, because the latter is operated as ROR, with a lower lifecycle emissions factor (see Song et al. [153] for a thorough discussion of lifecycle emissions) compared to the SAR-operated Ripogenus. GHG benefits are lower for Millinocket/Quakish than for Ripogenus because Millinocket/Quakish generates less electricity annually than Ripogenus.

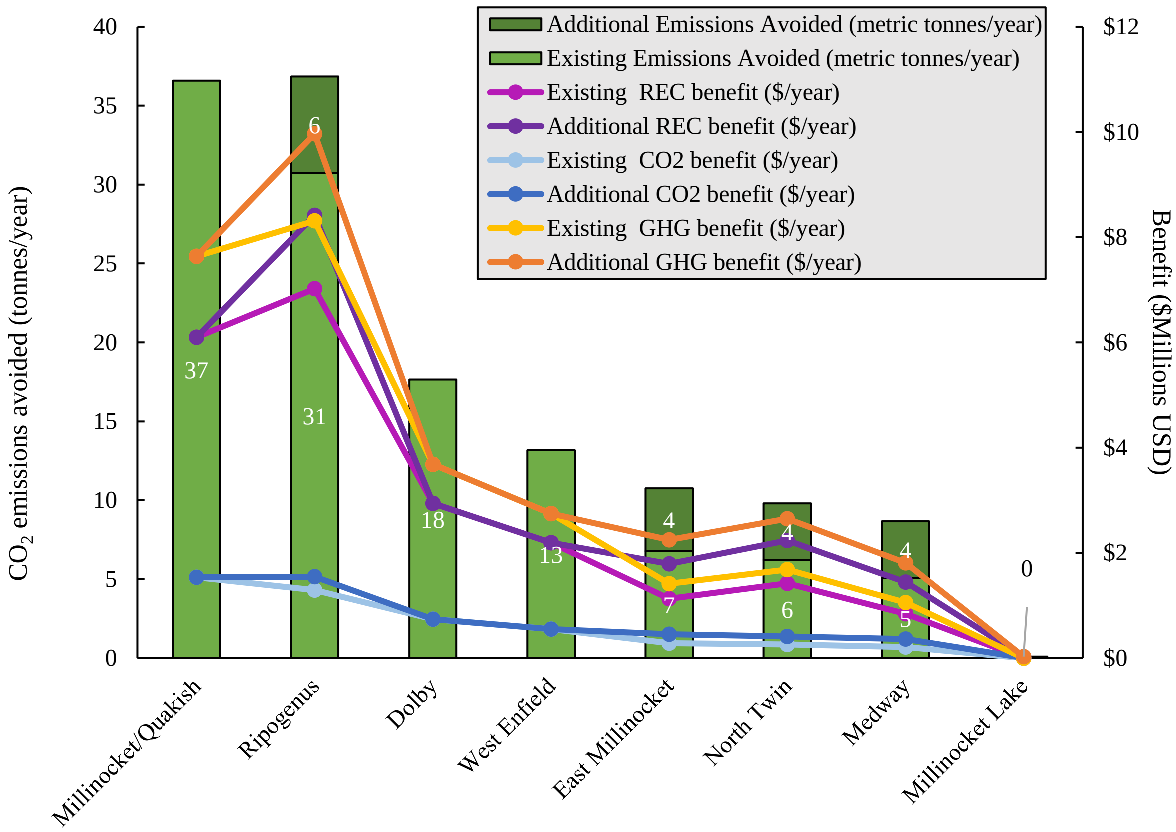

Figure 11. Estimated annual existing CO_2 emissions avoided (and estimated additional emissions avoided) with estimated existing annual GHG (REC + CO_2 price) benefits (assuming $30/MWh value for RECs, $42/tonne for CO_2) and estimated additional GHG (REC + CO_2 price) benefits.

3.3.3. NPV, IRR, BCR by Decision Alternative

'Improve Hydropower Generation' and 'Keep and Maintain' NPV estimates are comparable for Millinocket/Quakish, Dolby, and West Enfield (Figure 12). The estimates for Ripogenus, North Twin, and Medway are higher (5%, 17%, and 31%, respectively) for 'Improve Hydropower Generation' than for 'Keep and Maintain', and the estimate at East Millinocket Dam is 9% lower for 'Improve Hydropower Generation' than 'Keep and Maintain'. For Millinocket Lake, the NPV estimates are negative for both (though the NPV estimate is 52% higher for 'Keep and Maintain' than for 'Improve Hydropower Generation'), because the 220 kW of additional capacity does not generate enough electricity over the project's lifetime for revenues to offset costs. All decision alternatives for Millinocket Lake have a negative NPV, but dam removal is the closest to zero, at -$1 million (saving nearly $328,378) compared to Keep and Maintain. Only Ripogenus and Millinocket/Quakish see positive values for 'Improve Fish Passage' or

‘Improve Hydro AND Fish’. Dams that see a lower NPV under the ‘Improve Hydro AND Fish’ decision alternative include Millinocket/Quakish (6%,), Dolby (27%), West Enfield (20%), East Millinocket (12%), and Millinocket Lake (27%) because no additional generation is estimated for the site (see [107]). ‘Remove’ is the decision alternative with the lowest average NPV, indicating that the projects are all expected to lose money over the comparable 20-year lifetime because removal does not lead to revenue gain for the dam owner in this analysis.

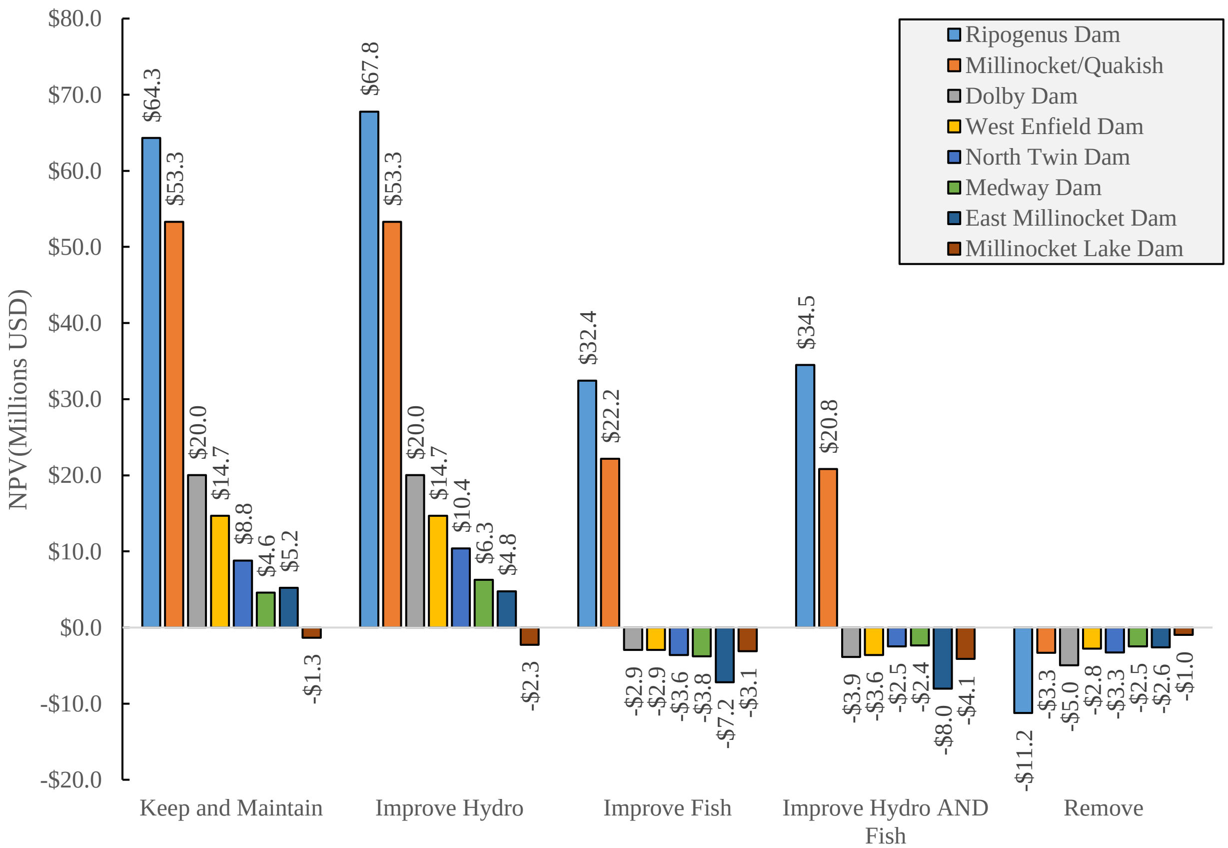

Figure 12. NPV results for five decision alternatives and 8 dams in Maine (20-year financial lifetime with a 6.2 % discount rate).

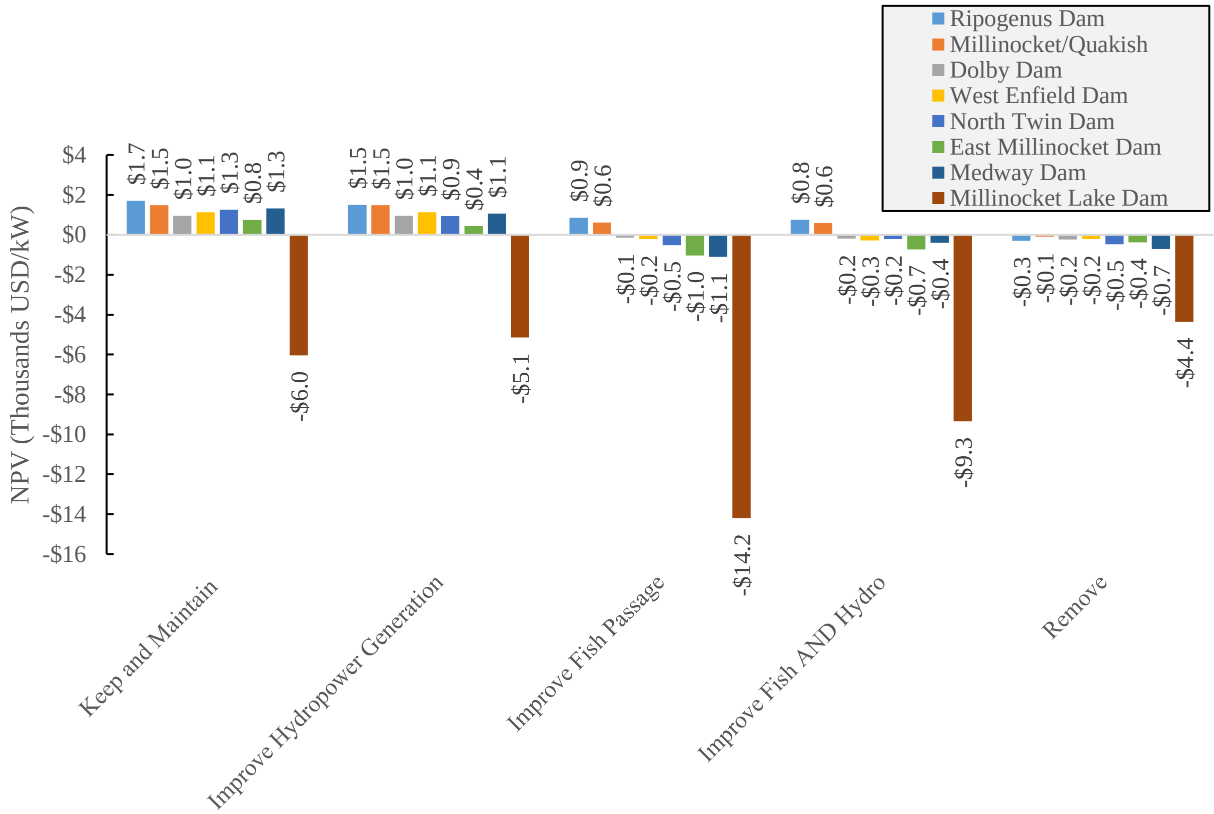

Figure 13. NPV (in thousands USD/kW, for comparison with Figure 12) for five decision alternatives and 8 dams in Maine (20-year financial lifetime with a 6.2 % discount rate).

Here, I focus briefly on the project cash flows I used to generate the NPV estimates presented in Figures 12 and 13, considering just one decision alternative ('Keep and Maintain') at a single dam (West Enfield) as an example (Figure 14). During relicensing (year 0), FERC licensing fees are required, along with minimal possible changes to maintain the structural integrity and safety of the dam. Recall, the C_{CAP} for 'Keep and Maintain' was estimated as equal to the ICC of licensing, without additional contingency costs. As expected, cash flow increases steadily from year 0 to 20 under the 'Keep and Maintain' (business-as-usual) decision alternative for the dam. The project cash flow for 'Keep and Maintain' becomes positive after year 2. IRR is positive after year 1. NPV for 'Keep and Maintain' is estimated to be $14.7 million, or $1,128/kW, if uncertain inputs (discount rate, wholesale electricity price) are considered static, with a project IRR of 68 percent. Under the NPV_{soc} scenario (recall, this includes CO_2 emissions savings valued using a mandatory market REC value of $30/MWh, and a carbon price of $42/tonne), NPV_{soc} for 'Keep and Maintain' is estimated to be $35.1 million, or $2,698/kW, given static inputs. IRR for NPV_{soc} is 72 percent. When considering multiple decision alternatives and multiple dams, IRR values are above 6.2 percent (discount rate, Table 22) for 'Keep and Maintain' and 'Improve Hydropower Generation' decision alternatives. IRR exceeds 100 percent at Ripogenus and Millinocket/Quakish for 'Keep and Maintain' and at Millinocket/Quakish for 'Improve Hydropower Generation'. Again, Ripogenus and Millinocket/Quakish are medium-scale hydropower dams, their larger power capacity seeing increased returns to scale as compared to the smaller-scale dams (e.g., East Millinocket, Medway). 'Improve Fish Passage' and 'Improve Hydro AND Fish' both have IRR values less than 6.2 percent for 5 of 7 powered dams (the 2 dams exceeding IRR of 6.2% for these decision alternatives are Ripogenus and Millinocket/Quakish). Recall, projects improving fish passage facilities or installing additional power capacity at a dam come with high capital expenditures, so if the existing or additional revenues from electricity generation are not enough to garner significant revenue over the lifetime of the project, the IRR will be less than the discount rate, even zero or negative. A licensee would likely look to find an IRR greater than or equal to the discount rate (here, 6.2 percent) as an indicator of a good investment, as long as the project has a positive NPV, and the larger the NPV, the more lucrative the investment.

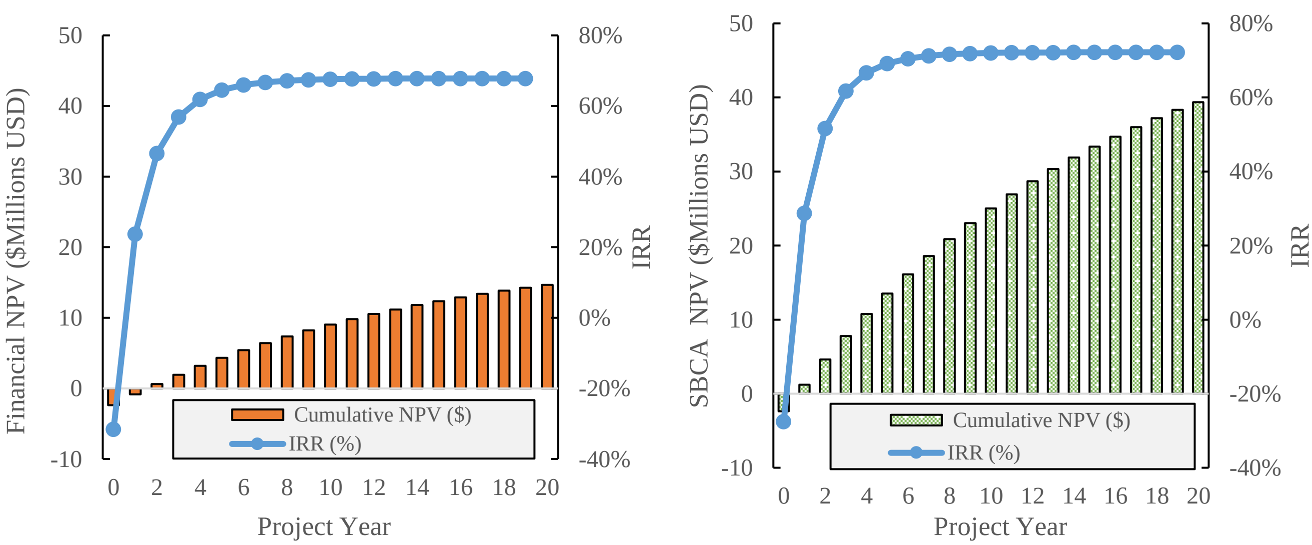

Figure 14. NPV Financial and NPV_{soc} project cash flows over a 20-year lifetime and a 6.2% discount rate for West Enfield under 'Keep and Maintain' decision alternative.

Table 22. IRR for existing powered dams and non-removal decision alternatives. Note: not including GHG benefits over a 20-year financial lifetime with a 6.2 percent discount rate.

Dam Name	Keep and Maintain	Improve Hydropower Generation	Improve Fish Passage	Improve Fish AND Hydro
Dolby Dam	**66%**	**66%**	5%	4%
East Millinocket Dam	**42%**	**12%**	-2%	1%
Medway Dam	**56%**	**17%**	0%	4%
Millinocket/Quakish	**113%**	**113%**	**13%**	**13%**
North Twin Dam	**64%**	**18%**	3%	5%
Ripogenus Dam	**130%**	**42%**	**16%**	**14%**
West Enfield Dam	**68%**	**68%**	4%	4%

Bold text indicates IRR > discount rate (6.2%).

BCR estimates (Table 23) provide an additional lens with which to interpret the story told by LCOE (Table 19) and IRR (Table 22). ‘Keep and Maintain’ has a BCR greater than 1 for 5 of 7 dams (LCOE and IRR results show that 7 of 8 dams are cost-competitive with electricity price ($0.035/kWh) and with IRR > discount rate). The 3 dams with BCR 0.8 – 0.9 for ‘Keep and Maintain’ are all on the smaller side, less than 7 MW. While North Twin is also less than 7 MW, we must remember that hydropower experiences returns to scale, so the extra 50 kW of capacity at North Twin seems to make all the difference, pushing the BCR value above 1.0. Somewhat similar to the results for LCOE (but unlike IRR) ‘Improve Hydropower Generation’ has benefits that exceed costs for 6 of 8 dams (East Millinocket and Millinocket Lake Dam are the exceptions). The difference with the LCOE results was that Medway Dam was not cost-competitive for ‘Improve Hydropower Generation’ based on a value of $0.038/kWh (and an electricity price of $0.035/kWh). IRR exceeded the discount rate (6.2%) at all 7 powered dam sites under ‘Improve Hydropower Generation’, but was lowest for East Millinocket, Medway, and North Twin, implying that while these hydropower plants saw positive revenues over their financial lifetimes, the costs over the still outweighed the benefits for East Millinocket and Millinocket Lake. As with IRR and LCOE, ‘Improve Fish Passage’ and ‘Improve Hydro AND Fish’ only have two dams meeting or exceeding the BCR threshold: Ripogenus and Millinocket/Quakish. ‘Remove’ has a BCR of 0 for all dam sites, indicating that it is not a cost-effective decision

Table 23. BCR for all dams and decision alternatives. Note: not including GHG benefits, over a 20-year financial lifetime with a 6.2 percent discount rate

Dam Name	Keep and Maintain	Improve Hydro	Improve Fish	Hydro AND Fish	Remove
Dolby Dam	**1.4**	**1.4**	0.6	0.6	0.0
East Millinocket Dam	0.8	0.8	0.3	0.5	0.0
Medway Dam	0.9	**1.1**	0.4	0.6	0.0
Millinocket/Quakish	**2.5**	**2.5**	**1.1**	**1.0°**	0.0
Millinocket Lake Dam	0.8	0.3	0.4	0.2	0.0
North Twin Dam	**1.1**	**1.2**	0.5	0.7	0.0
Ripogenus Dam	**2.9**	**2.3**	**1.2**	**1.2**	0.0
West Enfield Dam	**1.3**	**1.3**	0.6	0.5	0.0

Bold text indicates values exceeding the 1.0 threshold; ° = value is equal to the BCR threshold.

I calculated social NPV (NPV_{soc}) separately to compare generating asset values when GHG benefits are included. I focus on results for powered dams here because again the values for the NPV (Millinocket Lake) are all negative. For powered dams, NPV_{soc} ranges between $-11 million (Ripogenus, 'Remove) and $199 million (Ripogenus, 'Improve Hydro AND Fish') at powered dams, with a mean value of $56 million (Figure 15), while the per-unit NPV_{soc} values range between $-722/kW (Medway, 'Remove') and $7,738/kW (Medway, 'Improve Hydropower Generation'), with a mean value of $3,125/kW. The difference between NPV and NPV_{soc} is striking: the mean NPV_{soc} is 10 times higher than the mean NPV estimate. As with NPV, 'Keep and Maintain' and 'Improve Hydropower Generation' remain the top decision alternatives for NPV_{soc} where estimates are comparable for Millinocket/Quakish, Dolby, and West Enfield (Figure 15 - 16). The estimates for 'Improve Hydropower Generation' are higher than for 'Keep and Maintain' at Ripogenus (13%), North Twin (37%), Medway (42%), and East Millinocket (35%, a change from NPV, where East Millinocket was 9% lower for 'Improve Hydropower Generation). For Millinocket Lake, the NPV estimates are again negative for all decision alternatives. With NPV_{soc} all powered dams see positive values for 'Improve Fish Passage' or 'Improve Hydro AND Fish' (where NPV was only positive for Ripogenus and Millinocket/Quakish). 'Remove' is the decision alternative with no difference between NPV and NPV_{soc} estimates because there are no annual electricity generation revenues for which RECs may be sold, and no GHG emissions avoided to value with a carbon price.

RECs make a difference in NPV estimation, but a static REC price of $30/MWh is a generous assumption for Maine, calling for a sensitivity analysis. Likewise, the carbon price of $42/tonne CO_2 avoided is an uncertain input and calls for sensitivity analysis.

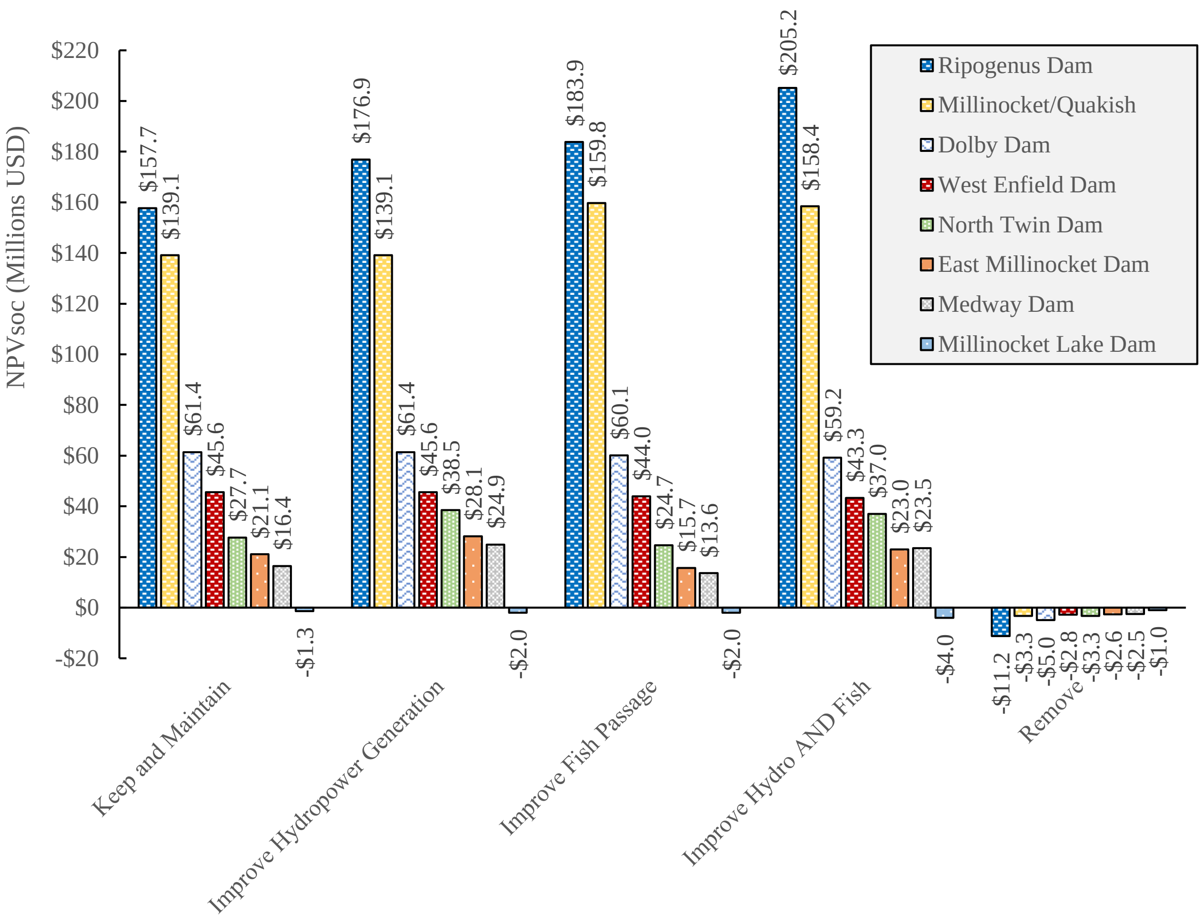

Figure 15. Social NPV (NPV_{soc}) for all dams, all decision alternatives (20-year financial lifetime, 6.2 % discount rate, $30/MWh REC price, and a carbon price of $42/tonne)

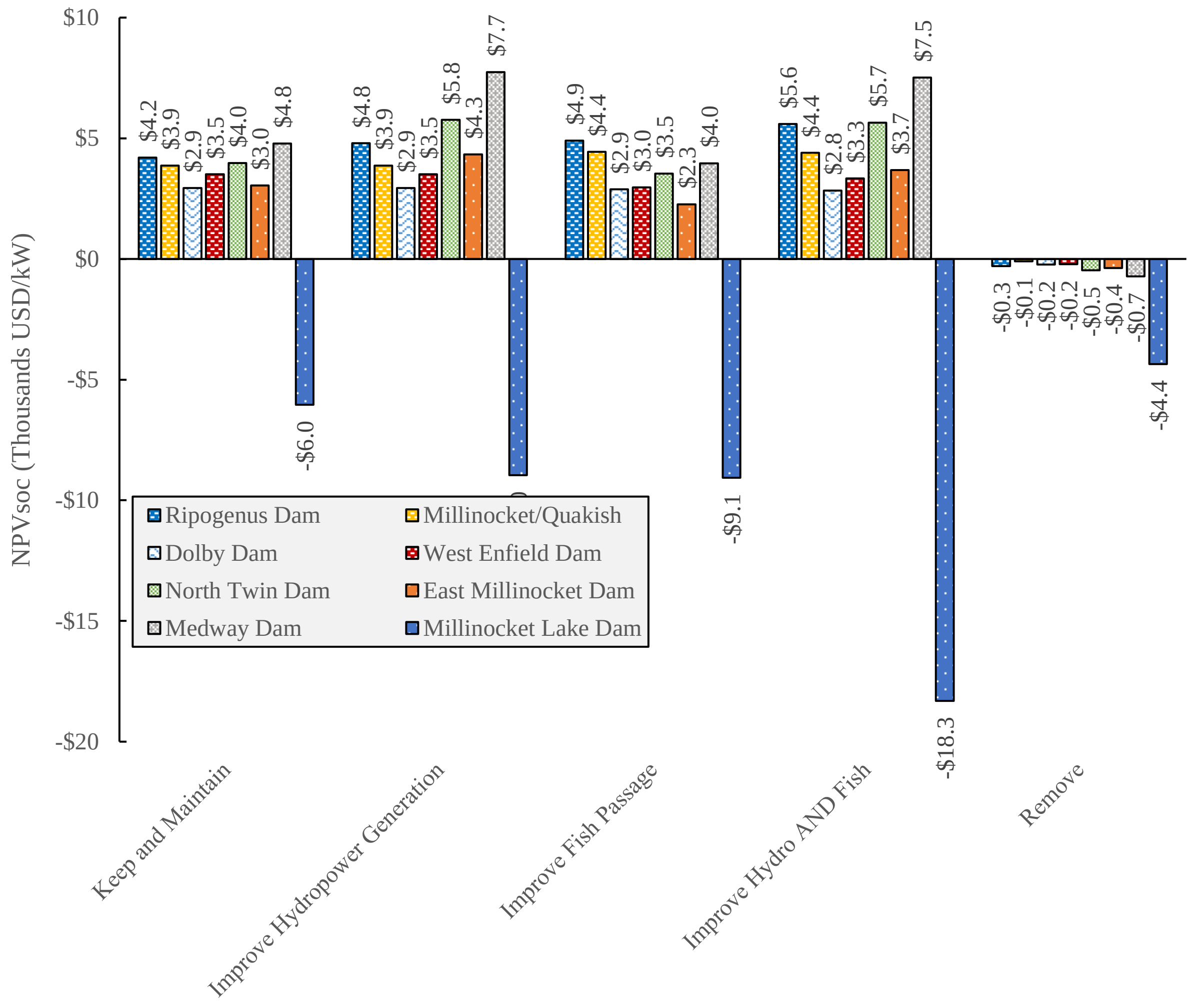

Figure 1116. Social NPV (NPV_{soc} in Thousands USD/kW) for all dams, all decision alternatives (20-year financial lifetime, 6.2 % discount rate, \$30/MWh REC price, and a carbon price of \$42/tonne).

3.3.4. West Enfield Project Sensitivity Analysis

For sensitivity analysis, I highlight a single dam (West Enfield) as an example, focusing on the business-as-usual case ('Keep and Maintain') for Monte Carlo simulation. Simulated NPV results range from \$15.1 million - \$41.9 million (\$1,165/kW - \$3,224/kW) (Figure 17), while NPV_{soc} results range from \$40.0 million to \$100.7 million (\$3,077/kW - \$7,751/kW) (Figure 18). The 25th percentile (discount rate = 5.6 percent, electricity price = \$0.03/kWh) has NPV equal to \$23.5 million (\$1,804/kW) and NPV_{soc} equal to \$59.8 million, or \$4,597/kW (with a REC price of \$0.02/kWh and a carbon price of \$41.48/ton). The mean simulated NPV estimate falls within the 50th percentile (discount rate = 6.8 percent, electricity price

= \$0.04/kWh), equal to \$26.8 million or \$2,065/kW (mean standard deviation of \$394/kW), where the mean simulated NPV_{soc} is \$66.5 million or \$5,114/kW, with a standard deviation of \$814/kW (REC price of \$0.03/kWh and a carbon price of \$54.06/tonne). Finally, at the 75th percentile (discount rate = 8.3 percent, electricity price = \$0.04/kWh) NPV is \$30.8 million (\$2,366/kW), while NPV_{soc} is \$74.0 million, or \$5,692/kW (with a REC price of \$0.04/kWh and a carbon price of \$70.43/tonne). The distribution of @Risk simulated NPV estimates follows the expected triangle shape (recall that the distributions for each of the uncertain inputs were triangular). The distribution of NPV_{soc} estimates is also triangle-shaped. If I had a more robust dataset (e.g., mean or standard deviation) for the uncertain inputs (e.g., discount rate), I might expect the simulated NPV estimates to be distributed more normally. As it was, I only had enough data to make judgments about the most appropriate minimum, maximum, and 'most likely' values, parameters sufficient for assuming triangular distributions for the uncertain inputs but insufficient for normal distribution assumptions.

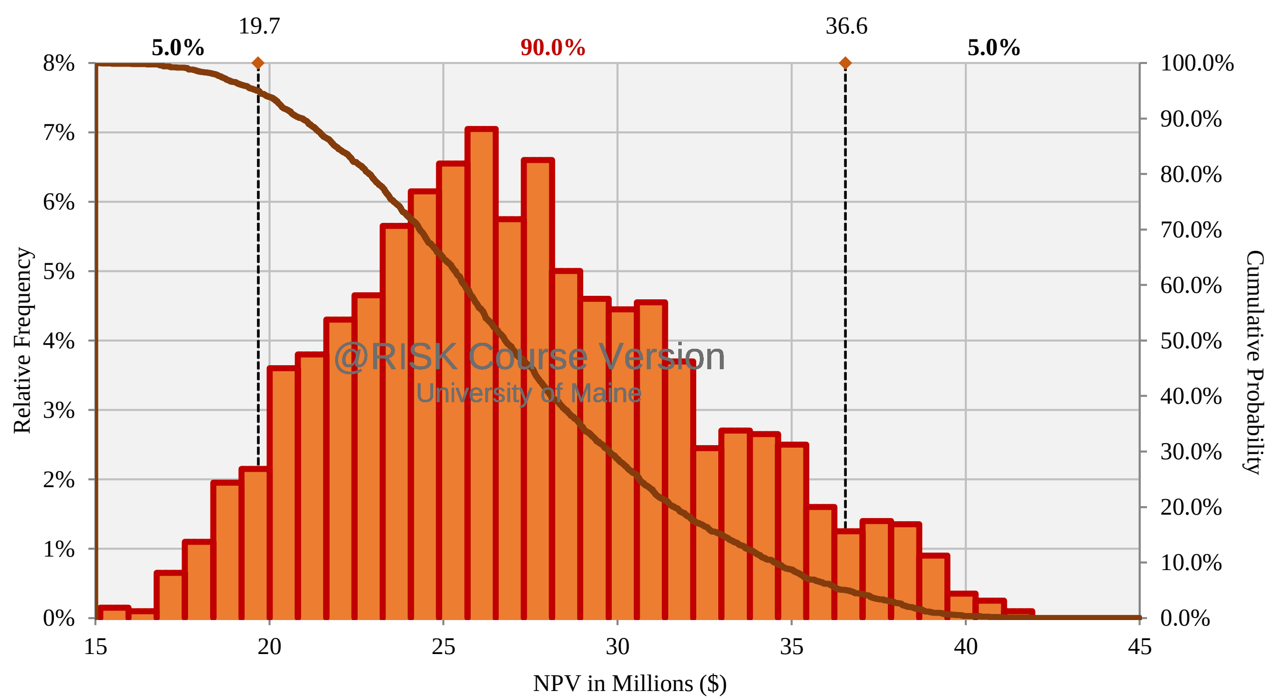

Figure 17. Monte Carlo results (2,000 simulations) for West Enfield 'Keep and Maintain' NPV.

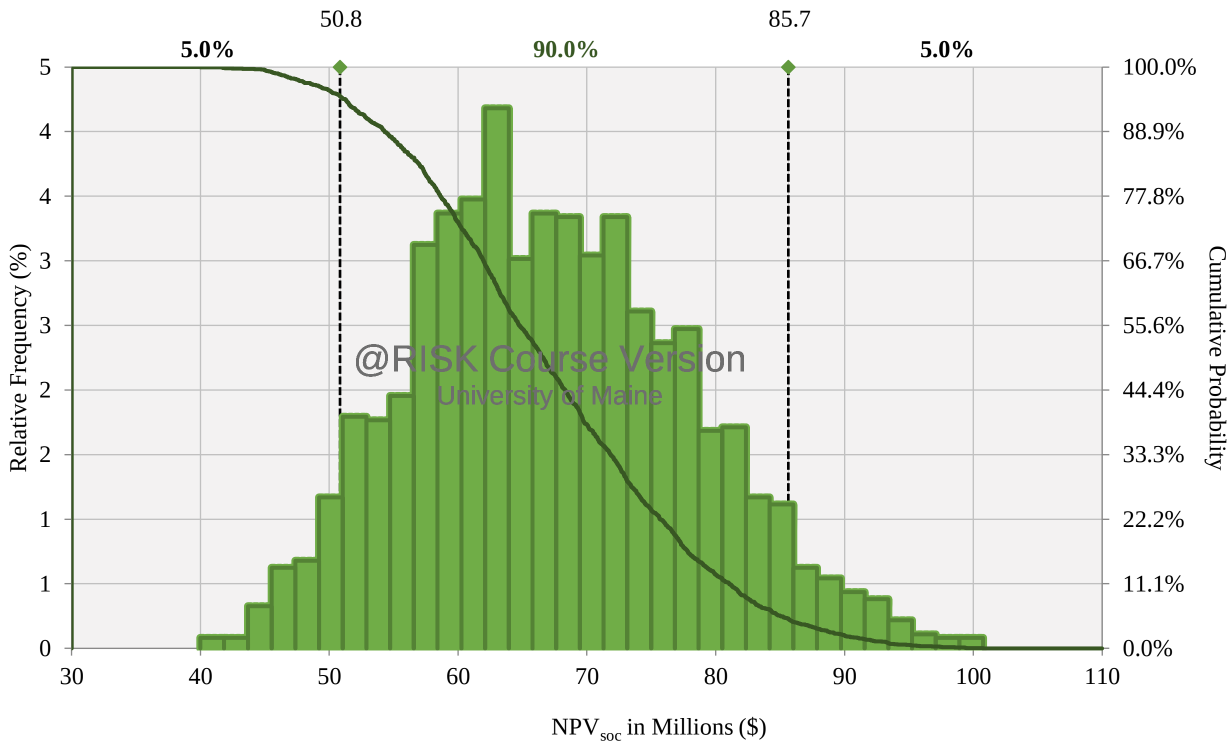

Figure 18. Monte Carlo results (2,000 simulations) for West Enfield 'Keep and Maintain' NPV_{soc}.

NPV is most sensitive to changes in electricity prices (Figure 19). Variation in electricity price is notably more pronounced for NPV than for NPV_{soc}, correlating to mean NPV outputs from $20.7 million to $34.4 million, and mean NPV_{soc} outputs ranging from $60.8 million to $74.6 million. The variation in discount rate correlates to mean NPV outputs ranging from $22.0 million - $32.7 million, while the mean NPV_{soc} outputs range from $55.6 million to $80.2 million (note: this is a greater range than for NPV because NPV_{soc} is most sensitive to discount rate). Variation in REC price correlates to mean NPV_{soc} outputs ranging from $56.0 million to $77.3 million, while variation in carbon price correlates to mean NPV_{soc} outputs ranging from $64.5 million to $69.4 million. NPV-input correlation graphs for 'Keep and Maintain' (as well as other decision alternatives) are in Appendix H.

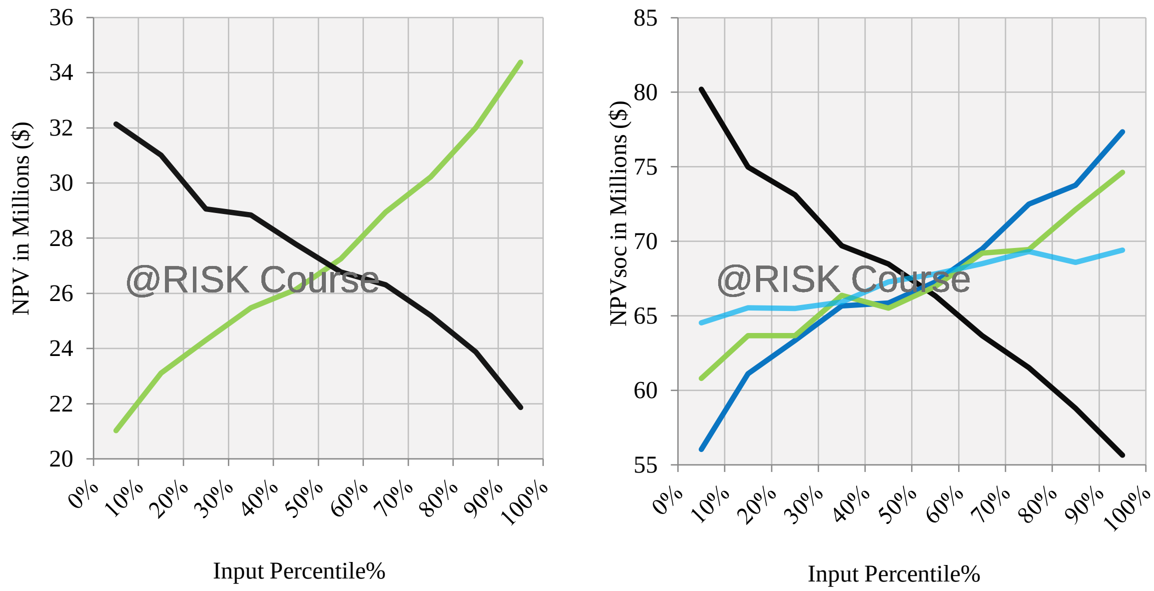

Figure 19. Spider graphs demonstrating sensitivity of NPV (left), NPV_{soc} (right) to uncertain inputs. Green = price of electricity, black = discount rate, blue = REC price, light blue = carbon price. Slope steepness corresponds to sensitivity to input (i.e., the closer the slope is to zero, the less sensitive NPV is to input changes).

3.4. Discussion

My contribution to the academic conversation about SHP project cost estimation is the exploration of explicit project (decision alternative) cash flows in the context of hydropower relicensing. Benefit-cost analysis (NPV assessment, lifetime project cash flows) is a classic form of decision support in the economic/business disciplines. I examine cash flows over a 20-year financial period for 5 decision alternatives each at a set of 8 dams coming up for relicensing in the next 10 years. Importantly, the dams and decision alternatives considered herein are consistent with the Multi-Criteria Decision Analysis model (another form of decision support) in Chapter 5. I assess NPV, BCR, and LCOE for the 5 decision alternatives and compare NPV (estimated based only on financial cash flows, not GHG benefits) with NPV_{soc} (estimated based on cash flows with yearly GHG benefits from both RECs for electricity generation and monetized lifecycle GHG emissions avoided) to give a more complete picture of the GHG benefits derived from hydroelectric generation.

In general, decision alternatives 'Keep and Maintain' and 'Improve Hydropower Generation' were cost-effective, with positive NPV at all powered dam sites (i.e., all except Millinocket Lake), ranging from

$4.6 million – $67.8 million, or $433/kW - $1,713/kW. Fish passage improvement alternative (i.e., ‘Improve Fish Passage’ and ‘Improve Hydro AND Fish’) NPV estimates are net negative for all dam sites except for Ripogenus ($32.4 million or $864/kW for ‘Improve Fish Passage’ and $34.5 million or $766/kW for ‘Improve Hydro AND Fish’) and Millinocket/Quakish ($22.2 million or $615/kW for ‘Improve Fish Passage’ and $20.8 million or $578/kW for ‘Improve Hydro AND Fish’), the two largest dams in the set, at 37.5 MW and 36 MW, respectively. At Ripogenus and Millinocket/Quakish, if fish passage improvements were required by FERC as a part of the operational license conditions, the estimated NPV for both sites would be almost halved from the ‘Keep and Maintain’ and ‘Improve Hydropower Generation’ alternatives. As expected, dam removal has a negative NPV at all powered dam sites, with a mean value of $-4.0 million, or $-354/kW. Millinocket Lake (an NPD) does not see NPV>1 for any decision alternative; however, it is licensed as a part of the Penobscot Mills Project, and it is possible that operating and maintaining the Millinocket Lake Dam is a necessary additional cost that the licensee bears as a requirement for the operation of the other four developments in the license.

Overall, my NPV estimates are lower than published values reviewed in Chapter 2 (e.g., [37], [38], [42], [44], [47]–[49], [52], [53], [94], [162], [163]), which have a mean NPV (converted and escalated to 2019 USD) of ~$3,800/kW (and a standard deviation of ~$2,600/kW): $9.4 million, or $599/kW (standard deviation of $10.0 million, or $641/kW) for all 8 dams and 5 decision alternatives. This makes sense because the studies reviewed in Chapter 2 disproportionately focus on NSD and NPD development projects, whereas I also consider powered dam improvements, business-as-usual, dam removal, and fish passage project options (with and without additional hydropower improvements). This means that even the more comparable decision alternative (in terms of construction, equipment) ‘Improve Hydropower Generation’ estimates (mean $25.3 million, or $1,073/kW) are, on average, 3.5 times lower than what the literature reports. This result highlights a need for more comprehensive and nuanced project cost assessment, particularly for existing powered dams. To my knowledge, no other study has explored SHP cash flows for an array of different project options (including fish passage and hydropower improvements) for existing powered dams. In particular, fish passage cost assessment is an area that could use more study.

Hall et al. [36] is the only study where we found fish passage cost estimates in Chapter 2, and other more recent studies (ORNL [11], [13], USBR [10], USACE [9]) all cite Hall et al. [36] for their fish passage modeling endeavors.

None of the reviewed papers in Chapter 2 monetize GHG benefits to NPV. Zhang et al. [13] discuss carbon pricing briefly, but ultimately leave GHG benefit monetization out of the ORNL-HEEA model altogether. So, this aspect of SHP cash flow assessment is also a unique contribution to the academic literature. My analysis highlights the importance of considering the cost-effectiveness of multiple decision alternatives (often left out of cash flow comparisons) in addition to the standard business-as-usual (i.e., 'Keep and Maintain'). My sensitivity analysis in @Risk has shown that NPV is very sensitive to both electricity price and discount rate, with the former driving much of the variation in the NPV output mean. Change in electricity price or discount rate could make the difference in deciding whether decision alternatives are cost-effective or not. This is especially true for those decision alternatives involving improvements to fish passage because the investment costs are comparatively higher, with little chance to recoup the costs over the project lifetime. Including social or GHG benefits (especially RECs) in the analysis of NPV may likewise determine the cost-effectiveness of the decision alternatives improving fish passage. NPV_{soc} seems to be more sensitive to REC price than electricity price (though like NPV, NPV_{soc} is still most sensitive to discount rate). The NPV_{soc} is least affected by carbon price in the sensitivity analysis, but carbon price does drive up the total GHG benefits value for each of the 8 dams. All 7 powered dams have NPV_{soc} estimates >1 for 'Improve Fish Passage' and 'Improve Hydro AND Fish'.

The BCR values for the decision alternatives at each dam provide some additional color to my analysis. The BCR for 'Keep and Maintain' and 'Improve Hydropower Generation' decision alternatives is >1.0 for Dolby, Millinocket/Quakish, North Twin, Ripogenus, and West Enfield (the larger dams in the set), indicating that these are cost-effective decision alternatives at those sites. While Medway has a BCR of 0.09 for 'Keep and Maintain', its BCR is equal to 1.1 for the 'Improve Hydropower Generation' decision alternative. In general, the decision alternatives including improvements to fish passage are not cost-effective, equaling or exceeding 1.0 only in the case of Millinocket/Quakish and Ripogenus dams. What this means is that the fish-related decision alternatives are often not cost-effective when not considering monetized GHG benefits. BCR >1 is a cutoff used for a few studies in the literature in broad-brush scoping for project cost-effectiveness. For Zhang et al. [13], USBR [10], and USACE [9], only sites with a BCR >1 are considered. Again, these studies are aimed at scoping NPDs for hydropower installation and do not consider powered dams or decision alternatives involving fish passage or removal. When monetized GHG benefits are considered, the 'Social BCR' (i.e., the BCR that compares total project GHG benefits with costs) is >1 for 'Improve Fish Passage' and 'Improve Hydro AND Fish' decision alternatives for Dolby and West Enfield, in addition to Ripogenus and Millinocket/Quakish. In this light, the fish-related decision alternatives would only by cost-ineffective at East Millinocket, North Twin, and Medway.

My LCOE estimates had a mean value of \$0.072/kWh across all decision alternatives, which is also lower than what we see in the SHP literature. The Chapter 2 literature review indicates that SHP values for LCOE (i.e., across all 15 studies reporting LCOE estimation) range from \$0.03/kWh - \$1.00/kWh. When we exclude the handful of outliers from Zhang et al. [13], the range collapses to \$0.03/kWh - \$0.29/kWh. My estimates for LCOE cover a wider range (\$0.014/kWh – \$0.670/kWh) than what the Ch. 2 suggests, but when I exclude Millinocket Lake, which never sees a positive NPV for any decision alternative, my LCOE estimate range becomes narrower than the range from the studies reviewed in Ch. 2 (\$0.01/kWh – \$0.068/kWh). LCOE reporting in the literature is patchy and incomplete; studies either do not list the discount rate used (e.g., [12], [43], [48]) or the project lifetime (e.g., [11]–[13], [103]), so I have little room to compare my estimates, except to say that based on my limited sample, LCOE seems to be lower overall for decision alternatives at existing powered dams. As with NPV and BCR, it would be useful to have comprehensive LCOE estimates for a suite of dam decision alternatives at existing SHP dams. LCOE is a cost-effectiveness indicator that is comparable across renewable technologies and could better characterize the comparative costs of hydropower in Maine's energy portfolio than NPV or BCR.

3.4.1. Limitations

Data collection for this study was a challenge and impacted the type of analysis I was able to perform. I decided on a bottom-up model based on my conclusions from Chapter 2 but I was limited to a cash flow model because of the available data. Hydraulic head and design flow information are challenging to find. Hydropower dam data, in general, are hard to find, with the FERC eLibrary being the best all-around source for information. FERC licenses are not formatted in a standard way; in fact, license issuance document organization differs considerably between licensees and across projects (single or multiple dams involved in the production of hydropower) and makes key project description information (e.g. C_{CAP}, annual electricity generation, hydraulic head, design flow) challenging to locate. This was the main reason I used regression equations from Hall et al. [36] to estimate ICC in my NPV assessment: hydraulic head information was challenging to locate, and the recent U.S.-based ICC estimation regressions (e.g. [11]–[13]) all use head and power capacity variables in their cost estimates. Fish passage almost certainly impacts annual O&M cost estimates as well, though I do not include it in my calculation (Eq. 31, [11]). O&M cost was challenging to deal with not only because no studies I reviewed included O&M values specific to fish passage (e.g., [10]–[13], [36], [37], [39], [42], [45]–[50], [53]–[55], [94]. I would expect O&M for decision alternatives with fish passage to have additional costs (in comparison to other alternatives discussed), particularly where facilities are mechanical (e.g., fish lift or elevator). While FERC licenses often provide information on fish mitigation prescriptions (as relevant), fish passage construction cost and O&M information is often not listed. Rather, the fish passage project cost estimation is a part of the Environmental Assessment (EA) step in FERC license review. I escalated initial cost and O&M values estimated using others' equations instead because Maine (and even New England) dam EAs in the last 30 years was a sample size too small to use in the development of coefficients to update Hall et al. [36] ICC values for fish passage construction, and there were no fish-passage specific data points with which to develop a unique O&M equation for fish passage that updates coefficients from O'Connor et al. [11].

REC price data collected from NREL were vague on the state level because they were originally collected from a proprietary source [136]. As a result, the values I picked to describe the distribution for sensitivity analysis were based on an educated guess. Carbon price data was also limited, but enough to identify a 'most likely' value (EPA [156]), minimum ([160]), and maximum ([157]). I do not consider other forms of hydropower incentives (i.e., tax credits, grants) in my financial analysis because there are few programs for hydropower developers still available at the time of writing. Though the Database of State Incentives for Renewables and Efficiency (DSIRE) [137] shows 48 states offering some form(s) of support for hydropower development, many state programs listed therein have since expired. The database lists 10 federal support programs, many of which have likewise expired or been repealed under the current U.S. presidential administration. There are no active incentive programs for which hydropower qualifies in the State of Maine. Finally, state and federal taxes have been left out of the calculations. I excluded them due to time concerns (and the fact that they would impact my estimates proportionately), but ultimately future research would include these values for a more accurate representation of NPV. Future work would also include cost data for other FERC-licensed hydropower dams in Maine to give an updated and comprehensive assessment of decision alternatives at all FERC dams sites.

3.4.2. A Word on Sustainability

RECs are granted to generators who produce no emissions from each MWh of generation. Carbon pricing highlights some of the additional GHG benefits without working through more complicated credit trading mechanisms (i.e., credits are usually granted up to a percentage of generation meeting a set standard, and certain projects qualify for a multiplier so that their credits are valued at 150 percent of the price of electricity), but the future analysis could certainly be more sophisticated than what I offer here. Hydroelectric facilities benefit measurably from REC programs, and certainly would benefit under carbon pricing schemes (though to a lesser extent), but a perception amongst anti-hydro groups is that SHPs are non-economical due to their smaller power capacities. However, this perception often ignores the alternative revenue stream or the option value of holding onto the power plant if electricity or REC prices rise, or if carbon pricing is finally put into effect in the U.S. as a means to internalize the present externalities (i.e., GHG emissions) in fossil fuel energy production and consumption. At most of the existing 7 hydropower dam sites, the business-as-usual alternative (i.e., ‘Keep and Maintain’ dam as-is) is a cost-effective project option, as is improving hydropower at many of the existing 7 hydropower dams with additional technical potential (see [107]), even where GHG benefits are excluded from project finances. Where fish-related decision alternatives are cost-ineffective at all but two dams, those projects may become economically viable where fish passage improvements are required if RECs or carbon pricing could provide additional revenue streams (e.g., states with RPS programs or voluntary green power markets). Considering that hydropower is already economically competitive with solar or wind because of its lower operation and maintenance costs extended over a longer lifetime (see for example [61], [96]), it seems that many of the existing hydropower dams I assessed are here to stay, at least for the length of another license. With that in mind, people who oppose hydropower due to the ecological impacts it has on the local environment and threatened and endangered species may be encouraged to learn that improved REC markets and carbon pricing could help encourage more hydropower owners to react more favorably to fish passage requests/mandates.

While my analysis on carbon pricing and RECs suggest that further work on dataset compilation is needed, the dataset I created for hydroelectric power plants in the Penobscot River could easily be extended to include the rest of the hydropower dams in the State of Maine. This would be a positive next step in helping Maine stakeholders and policymakers think about the role of Maine's hydropower fleet in the future. Conversations with Maine stakeholders indicate that there is a growing interest in the comparative costs of other non-hydro renewable energy technologies and the general possibility of replacing hydropower dams as they are decommissioned or removed. There is a demand for more robust comparative cost information as Maine's energy mix moves away from fossil fuels to more renewable energy sources under the new and increased RPS goals.

4.0. A REVIEW OF GROUP PARTICIPATORY MULTI-CRITERIA DECISION ANALYSIS (MCDA) FOR HYDROPOWER DAM DECISION SUPPORT[15]

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Abstract

Hydropower dam decisions involve multiple decision alternatives and associated criteria (e.g. fish survival, annual electricity generation, annuitized project cost, river recreation area, and reservoir storage), and decision makers are often challenged by the need to balance competing management objectives. Moreover, hydropower dam decisions are rarely made by one decision-maker in isolation; rather, each decision requires a group participatory process of some kind. We review 25 studies that document the use of a Multi-Criteria Decision Analysis (MCDA) or related decision support model for water resource decisions. We find discussion of participatory MCDA limited, with emphasis on modeling rather than processes used to engage decision-makers. Where group participation is described, the focus is general (who attended, how many workshops), and not on the specific deliberation process to reach agreement in a group setting. Likewise, we observe that a systematic evaluation of an MCDA approach's effectiveness for supporting such a process is typically missing in application studies. We note patterns in

[15] This chapter is an in-progress journal manuscript that Dr. Sharon Klein and I have been working on together for the last three years and is in the final stages of revision prior to peer-reviewed journal submission. Some of the wording in this chapter is hers, but due to the iterative nature of our collaboration over the past three years, it is too difficult to separate out which words are hers and which are mine. We are co-authors on this chapter, with the bulk of the writing, and all tables and figures completed by me.

participatory decision-making application studies, including whether decision makers were involved in: (a) decision criteria identification, (b) decision alternative identification, (c) rating criteria, and/or d) rating alternatives. We also assess the decision support model suitability for participation using a custom two-dimensional approach, which suggests that overall, weighted sum is the model type most suitable for this decision context. The results of this analysis help inform MCDA model selection for use with stakeholder groups in river management decisions involving hydropower dams.

Keywords: Multi-Criteria Decision Analysis, MCDA, decision support, hydropower dams, renewable energy, water resource management

4.1. Introduction

Resource management questions involving rivers and dams present problems characterized by differing user objectives, disagreement, and high levels of complexity or uncertainty [164]. Decisions involving hydroelectric dams are particularly challenging, requiring decision-makers (DMs) to balance considerations (decision criteria, hereafter "Criteria") for hydropower generation with other benefits (e.g., flood control, crop irrigation, drinking water). Furthermore, decisions about impounded water resources have the potential to affect a diverse range of stakeholders. The variety of water-based interests and uses creates the potential for conflict between DMs representing different stakeholder groups, but it also presents an opportunity to explore adaptive and site-specific management strategies. Davies et al. argue that Multi-Criteria Decision Analysis (MCDA) is a unique decision-support tool due to its usefulness in facilitating structured and transparent discussions between groups [71]. Due to the number and variety of DMs and Criteria (many of which are challenging to monetize) involved in water resource management decisions, MCDA applied in group environments (in which DMs interact directly with the MCDA as a group) may be useful for improving dam decision processes and outcomes. Dam decisions often involve conflicting DM opinions, interests, and values; they are not made by DMs operating in isolation.

We review 9 general MCDA approaches (section 4.2.) and 25 group participatory decision-making application studies (focusing on MCDA) that involve water resources and renewable electricity generation (sections 4.4.). While comparing MCDA approaches has become increasingly common in the literature (see for example [165]–[168]), the evaluative comparison of *group* participatory methods in conjunction with MCDA is newer, especially in hydropower dam decision-making. We classify applications of MCDA and other forms of participatory decision support for water resources and renewable electricity generation and rate them for (a) depth of engagement and (b) modeling complexity (section 4.3.). We combine these rating systems to compare studies using a 2-dimensional plane (Section 4.5.) to identify appropriate group participatory MCDA methods for hydropower dam decision-making. We aim to identify MCDA models that may be used with limited researcher support, and that may easily be coupled with a group participatory process.

4.2. Overview of MCDA Modeling Approaches

Broadly, MCDA is a form of decision support that provides a structured framework for decision-making, taking into account: decision alternatives (e.g., remove dam, improve hydropower generation, improve fish passage; hereafter "Alternatives"), Criteria data, and stakeholder or DM preferences [169][170]. There are 6 general steps (Figure 20) [71], [166], [171]: 1) Define the problem, Criteria, Alternatives; 2) Collect/harmonize Criteria data (make units consistent) in a decision matrix (n x m table with m columns) populated with Criteria data and n rows for Alternatives; 3) Normalize Criteria data so different units of measurement are comparable; 4) Elicit and quantify DM preferences (e.g., surveys, interviews, group negotiation); 5) Mathematically aggregate DM Preference data ("weights") and normalized Criteria data; 6) Rank Alternatives (cardinal or ordinal) based on Step 5 results. MCDA includes a family of decision approaches (Table 24) that rank Alternatives according to multiple Criteria and synthesize those rankings into a numerical score for each Alternative.

In the following paragraphs, we provide an additional explanation of only those methods that appear in the 25 water resource/hydropower application studies we review in section 4.4.

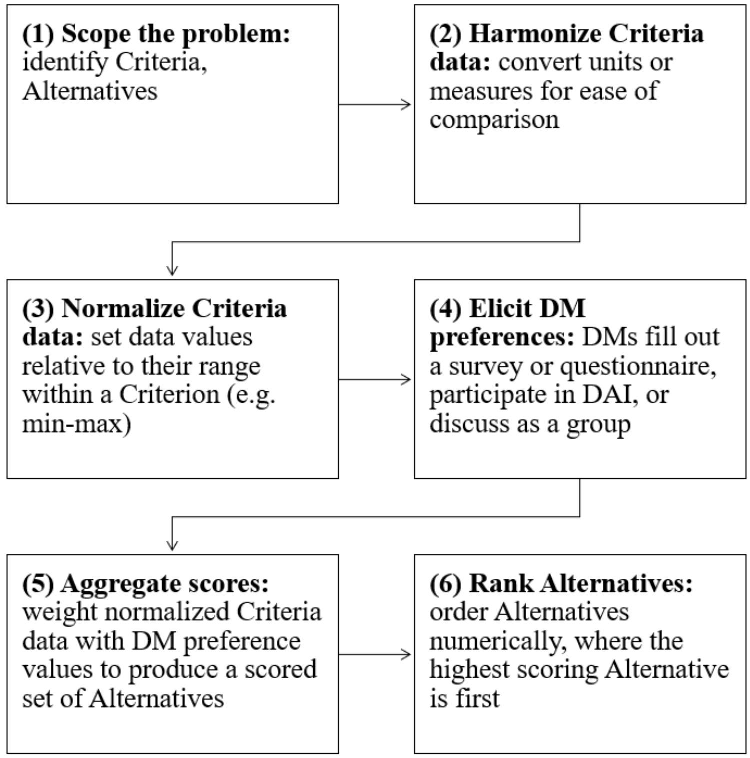


Figure 20. General steps for performing MCDA (actual individual steps vary by approach).

Table 24. Summary of main MCDA modeling approaches.

Approach	Description	(Step 3) Data Normal-ization	(Step 4) Preference Elicitation	(Step 5) Aggregation Method	(Step 6) Ranking	Studies
Weighted Sum (WS)	Classical form of MCDA; normalizes Criteria values to 0 to 1 scale; calculates the sum-product of DM preference weights and normalized Criteria scores for a score between 0 and 1 of each Alternative; ranks Alternatives based on these scores.	Eq. 44-46	Any	WS	Eq. 48, Cardinal	[172], [173]
Weighted Product (WP)*	Classical form of MCDA; normalization not necessary; calculates the product of Criteria data raised to the power of DM preference weights for each Alternative; ranks Alternatives based on these scores.	Eq. 44-46	Any	WP	Eq. 49, Cardinal	[173]–[175]
Multi-Attribute Utility Theory (MAUT)*	Developed from Expected Utility Theory; incorporates optimization amongst a set of tradeoffs; designed to handle partial (risk-based) utilities for each Criterion and a total utility function for the Alternative choice; uses non-deterministic preferences; explicitly handles risk and uncertainty.	Eq. 44-45	Risk-based questionnaire	Utility Function	Ordinal	[176]
Multi-Attribute Value Theory (MAVT)	Nearly identical to MAUT, but uses a deterministic value function rather than utility function to aggregate preferences; requires explicit preferences rather than risk-based utilities.	Eq. 44-45	Any	Value Function	Cardinal	[177]
ELection Et Choix Traduisant la REalité (ELECTRE)*	Outranking approach includes multiple methodologies (e.g. I, II, III, IV) using concordance and discordance indices to assess DM satisfaction with Criteria in an ordinal way (e.g. Criterion 1 is twice as good as Criterion2).	Eq. 46	Pairwise as appropriate	Concordance or discordance index	Ordinal	[172], [174], [178]
Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE)	Outranking approach; includes multiple methodologies (e.g. I, II, III, and GAIA); elicits DM preferences based on WS-like scores; then uses outranking flows to translate preferences into single-Criterion preference degrees (akin to partial utilities), calculated to be above, below, or between indifference and preference thresholds between 0 and 1	Eq. 46	Pairwise	Eq. 50-52	Eq. 50-52, Ordinal	[173], [179]–[181]

Table 24. (Continued)

Approach	Description	(Step 3) Data Normal-ization	(Step 4) Preference Elicitation	(Step 5) Aggregation Method	(Step 6) Ranking	Studies
Technique Ordering Preferences by Similarity to Ideal Solutions (TOPSIS)*	Measures the distance of each real Alternative (defined by a normalized set of Criteria) to a hypothetical 'positive ideal' Alternative (defined by the 'best' normalized Criteria data values) and distance from a hypothetical 'negative ideal' Alternative (defined by the 'worst' normalized Criteria values); these distances are used to rank the real Alternatives.	Eq. 46	Pairwise	WS	Cardinal	[172]–[174]
Analytical Hierarchy Process (AHP)	A pairwise preference elicitation technique; uses hierarchical decision problem structuring; ratings are consolidated using the geometric mean method before ranking using WS.	Eq. 44-46	Pairwise	WS	Cardinal	[182]–[185]
Novel Approach to Imprecise Assessment and Decision Environments (NAIADE)	A pairwise preference elicitation technique; specifically designed for groups; software-dependent; uses semantic distance (i.e. distance between preference ratings on a Likert scale) derived from probability density functions (e.g. standard normal bell curve) ranging from 0 to 1; explicitly includes participant preference comparison as a process step (results in a visual map of 'coalitions' amongst participants).	Eq. 44-46	Pairwise	WS	Cardinal	[92], [93], [186]

* Our water resource/hydropower-focused literature review did not yield any studies using this method; therefore, we do not include additional information about this method in this paper.

$$r_{ij} = \frac{x_{ij} - x_{min}}{x_{max} - x_{min}} \quad where\ x_{min} is\ preferred, \tag{44}$$

and where i = criterion, j = alternative.

$$r_{ij} = \frac{x_{\max} - x_{ij}}{x_{max} - x_{min}} \quad where\ x_{max}\ is\ preferred, \tag{45}$$

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}\ ,\ for\ i = 1, 2, 3, \dots, n \tag{46}$$

$$w = \frac{1}{N}, \quad where\ N = total\ number\ of\ criteria\ \ (x) \tag{47}$$

$$A_j = \sum_{j=1}^{M} w_i r_{ij}\ ,\ for\ i = 1, 2, 3, \dots, n \tag{48}$$

where A is the set of all Alternatives.

$$A_j = \prod_{j=1}^{M} r_{ij}^{w_i}\ ,\ for\ i = 1, 2, 3, \dots, n \tag{49}$$

$$\forall\ j, k\ \in A, \quad \pi(j, k) = \sum_{i=1}^{M} w_i P_i\left(r_{ij} - r_{ik}\right) \quad for\ i = 1, 2, 3, \dots, n \tag{50}$$

where π *= global preference index;* $P_i(j, k)$ *= Alternative-Criteria preference value;* w_i *= weight* [181].

$$\phi^{+/-}(j) = \frac{1}{A-1} \sum_{k \in A} \pi\left(x_j, x_k\right) \tag{51}$$

where ϕ *= outranking flow.*

$$\phi(j) = \phi^{+}(j) - \phi^{-}(j) \tag{52}$$

All methods presented in Table 24 use some variation of Eq. 44 – 46 or similar (see also [61], [175]) to normalize Criteria data at some point during the process. Normalized Criteria values can be weighted using equal (Equation 47) [61], hypothetical, or elicited DM preference weights. Approaches with a dedicated and complex preference elicitation and modeling procedure (e.g., PROMETHEE, AHP, NAIADE) also include a normalization or standardization step for preference data leading to preference weights (e.g., division by vector sum for AHP; preference intensity index for NAIADE). While some methods (e.g. PROMETHEE) use their own final ranking technique (step 6), many (e.g. AHP, NAIADE) use WS (Eq. 48 [61], [187]) to generate the ranked outcome or final recommendation. Even MAVT may be a form of WS in cases where the value function is linear and preferences are simplified to be scalar rather than functions. This is not surprising, as WS is the most ‘elementary’ approach to MCDA [173], from which most other approaches appear to build. One main limitation of WS that other methods attempt to overcome is it uses total compensation (1:1 tradeoffs [188]) between Criteria [167], which means that as one Criterion increases in importance, another Criterion's importance must decrease, with the highest-ranked Alternative interpreted as 'first best'. While some consider this problematic [188], in some cases, compensation can be useful in highlighting real-world tradeoffs for DMs (a 1:1 consideration forces prioritization), underscoring the notion of compromise. On a practical note, the linear additive representation of preference values in WS may translate well for DMs who are not comfortable with interpreting more complex mathematical models.

While MAUT and MAVT also use total compensation and a 'first best' approach [167][187], they allow more complex modeling of nuances in DM preferences than WS through utility or value functions that do not have to be linear. The substantive differences between MAVT and MAUT are: 1) MAVT uses a value function instead of a utility function, distinguished by *certainty associated with DM preferences* (i.e., MAVT does not consider risk attitudes) [189], making its ranking cardinal, whereas the final ranking for MAUT is ordinal; 2) MAVT does not require lottery-style questions in preference elicitation like MAUT does, because it does not consider utility as a probability distribution [189]. Researchers often do not clearly distinguish between MAVT and MAUT, likely because MAVT is simply a specific case of MAUT. The MAUT/MAVT family of models is beloved by many decision theorists for its consistency with the economic theory of preferences (transitivity, independence of irrelevant Alternatives) and the relation of those preferences to risk [185], [190].

In contrast to WS, PROMETHEE, AHP, and NAIADE all include highly involved preference elicitation and modeling procedures with pairwise comparisons of Alternatives under a single Criterion [181], [187], [182]–[184], [93],[186]. PROMETHEE and NAIADE normalize Criteria data and apply a version of WS (Eq. 48 for PROMETHEE) *before* pairwise comparisons, while AHP applies Criteria normalization and WS aggregation *after* pairwise comparisons (or not at all). PROMETHEE comes from a family of 'outranking approaches', which are centered on the idea that one Alternative (j) must be at least as good as another (k) to outrank it [178] and use pairwise comparisons to identify preference thresholds [181]: *indifference* (i.e., neutral, or 0, where DM is indifferent between Alternatives j and k), *strict* *preference* (i.e., positive (>0 to 1), where above j is strictly preferred over k), and *strict non-preference* (i.e., negative (<0 to -1), where below k is strictly preferred over j). These preference thresholds overcome the total compensation limitation of WS and aid the DM in identifying Criteria-Alternative specific preference values (e.g., preference for Alternative *j* versus Alternative *k* under Criterion I, or $P_i(j,k)$ in Eq. 50).

NAIADE and AHP do not use preference thresholds. Instead, NAIADE first applies equal preference weights to normalized criteria data (Eq. 62-63), resulting in an "impact matrix", which is used to calculate WS-based rankings for Alternatives. Then, DMs undergo pairwise comparisons similar to PROMETHEE, but with Likert-scale ratings (e.g. strongly preferred = 5, preferred = 4, indifferent = 3, not preferred = 2, strongly not preferred = 1) instead of indifference thresholds. Alternatively, AHP does not use an impact matrix and administers pairwise comparisons on a 9-point 'fundamental scale' designed by Thomas Saaty [182]–[184]: 1=equally preferred, 5= strongly preferred, 9=extremely preferred. Preference values from AHP's scale are entered into a 'raw' pairwise comparison preference matrix for each Criterion (i.e., a matrix with each Alternative listed along the rows and columns, where the cell comparing Alternative A to Alternative A would have a 1 and the cell comparing Alternative A to Alternative B would have a value greater than 1 on the fundamental scale (e.g., 3) if A is preferred over B or the reciprocal of a value greater than 1 if B is preferred over A (e.g., 1/3)).

After the pairwise comparisons, each method has a unique process of achieving an 'answer'. PROMETHEE asks the DM to directly weigh the Criteria and then creates a global preference index (Eq. 50), where 'global' refers to broad preferences for Criteria (that are not Alternative-specific), rather than the 'local' Alternative-specific Criteria preference values elicited in the pairwise comparisons. AHP also uses a local-global preference modeling approach, wherein each 'raw' element in each Alternative preference matrix for each Criterion is divided by the sum of its column and averaged row by row (i.e., standardization) to achieve a 'local preference' weight [191]. This standardization process is repeated for pure Criterion vs. Criterion comparisons (e.g., Criteria are listed down the rows and columns, instead of Alternatives) to achieve a set of 'global preference' weights specific to each Criterion.

AHP then multiplies local and global preferences and sums them to yield the final DM preference weight [184] (similar to WS but with local and global preferences and no Criteria data).

NAIADE diverges from this local-global pattern because NAIADE is the only dedicated group preference elicitation procedure from Table 24. NAIADE assembles an "equity matrix" whose rows represent preference ratings from the pairwise comparison by each DM present in the group activity (e.g. dam owners, agencies, farmers), and the columns represent Alternatives. A "similarity matrix" indexes DM preferences for Alternatives in a pairwise manner (e.g., rows and columns of DM_1, DM_2, where the cell comparing DM_1 to $DM_1 = 0$ and the cell comparing DM_1 to DM_2 is between 0 and 1, with values closer to 0 indicating greater agreement between DMs). The semantic distance between different DM preference ratings is calculated based on the similarity of one preference judgment to another [93],[186] (i.e., Likert scale ratings occupying an equal amount of space on a line extending from 0 to 1, where "strongly preferred" occupies the space between 0.8 and 1). These numerical ranges ('fuzzy' preference values) are used to calculate the semantic distances between DM preferences, which are used to highlight areas of overlap (i.e., facilitating negotiation) and resolve conflicts between DMs over preferences. The similarity matrix is often paired with a dendrogram of coalitions, a visual representation of preference similarity generated using the NAIADE software (NAIADE is the only approach from Table 24 that is strictly software-based [186]).

NAIADE's final ranking (Step 6 from Figure 20) has two parts: (1) a WS-based equal preference ranking, and (2) a group DM ranking, based on the agreement between DMs over 'top' priorities [93]. PROMETHEE's final ranking process is more involved, producing partial (i.e., Alternative-specific) positive, $\phi^+(j)$, and negative, $\phi^-(j)$, outranking flows (i.e., relative order) between Alternatives (Eq. 67) [180], [181], where: j outranks k if: $\phi^+(j) > \phi^+(k)\ and\ \phi^-(j) < \phi^-(k),$ if $\phi^+(j) > \phi^+(k)\ and\ \phi^-(j) = \phi^-(k),$ or if $\phi^+(j) = \phi^+(k)\ and\ \phi^-(j) < \phi^-(k)$ [192]. Positive (ϕ^+) outranking flows show how an Alternative *outranks* other Alternatives, and negative (ϕ^-) outranking flows show how an Alternative is *outranked by* other Alternatives [178]. Outranking flows help validate consistency across or agreement between an individual DM's judgments. The partial outranking of Alternatives helps determine which Alternatives to exclude (usually because the DM finds him/herself indifferent between Alternatives or certain Alternatives to be incomparable altogether). The net outranking flow (Eq. 124, from PROMETHEE II [180], [181]) is calculated over the full set of Alternatives *A*, and can be thought of as the PROMETHEE final MCDA score. AHP also includes a consistency check before ranking Alternatives [91], which calculates a consistency ratio through this procedure: 1) calculate a vector of dot products (Criterion-specific consistency values) for each Alternative row of the 'raw' preference matrix and the row average of the 'standardized' matrix; 2) divide each Criterion-specific consistency value by the total number of Alternatives; 3) subtract the total number of Alternatives; 4) divide by the total number of Alternatives less one; 5) compare this 'consistency index' value to a random index (pre-specified by Saaty), where up to 10% inconsistency (i.e., consistency ratio ≤ 0.1) is considered acceptable. Sometimes the consistency check and final preference values are the final 'answer' for AHP. In other cases, criteria data are included in a final WS ranking calculation using the preference weights derived from AHP.

Overall, WS is simple and transparent, forcing the idea of tradeoffs through total linear compensation between Criteria, but does not capture nuances or complexities in DM preferences. MAUT/MAVT are consistent with utility and risk preference theories and enable complex modeling of DM preferences, making them conceptually and mathematically very strong, but perhaps challenging to use in practice with DMs due to interpretation, which is cognitively demanding. PROMETHEE, AHP, and NAIADE all use WS in some part of the aggregation process, with their strengths and difference lying in the way DM preferences are elicited. PROMETHEE is valuable for helping to narrow the set of Criteria or Alternatives to something more manageable. However, a different preference elicitation method must be used if the purpose is to choose an Alternative [193]. AHP is the most commonly used approach for environmental applications [187] and employs what may be the most thorough preference elicitation procedure, but it is also reportedly fatiguing to use in practice [90]. NAIADE is the most infrequently cited approach [187] but is the only approach deliberately designed for groups. It is important to note that NAIADE does require a specific software (with considerable instructional material), putting it at a disadvantage compared to other approaches.

Despite the many ways in which DM preferences can be elicited, most published MCDA studies actually use simulated preferences rather than eliciting them from DMs [194]. Academics and practitioners have begun to recognize the need for meaningful participatory approaches, and there is an ongoing call from academics and resource managers involved in public decision-making processes to actively involve DMs in all stages of the management process [75], [195], [196]. The incorporation of DM perspectives in MCDA and other decision support approaches appears to be gaining momentum in freshwater resource management and energy decision-making contexts internationally [87], [197], [198]. Participatory MCDA has also been used to gauge preferences for irrigation infrastructure Alternatives [199], reservoir level regulation [200], and other water resource management decisions [18, 21, 22]. However, as the participatory MCDA literature grows, there is still a lack of studies that compare participatory (especially group, not just individual) MCDA approaches for use with actual DMs in hydropower dam decisions. Besides, most comparative studies only include *ex-ante* evaluation, and not *ex-post*, except for Marttunen et al. [171] who classify their past studies by the (a) integration of MCDA into the planning or decision–making process, and (b) interactivity of DMs in MCDA (i.e., what roles are DMs taking on?). However, we have not seen this classification applied *ex-ante*.

Few, if any, of the application studies we review justify their methodological choices using practical, process-based selection criteria. Other than the reviews by Peniwati [191] and Cinelli et al. [188], we were challenged to find papers that explain both the technical and practical differences between MCDA approaches in a broadly understandable way, with consideration for applying MCDA in participatory settings. Several studies categorize and/or compare MCDA methods for different purposes [166]–[168] [202] [173]. For example, Huang et al. [187] review a decade (2000-2009) of 312 MCDA studies and methodological trends within the environmental sciences, classifying them by decision or intervention type, including 51 MAVT (6%, 14% of energy decision-making and water quality/management studies, respectively); 14 AHP (42%, 19%), and 25 PROMETHEE (12%, 5%) studies. Huang et al. include WS indirectly as a specific type of MAVT and as a first step in the NAIADE process (aggregated within 23

‘Other’ studies). While this information is useful for knowing how frequently these methods are used in environmental applications, it does not tell us which methods *should* be used for these applications.

We begin to fill this gap by proposing two key dimensions on which to evaluate MCDA models and participatory approaches for use with DMs in a group setting (section 4.3.): Model Complexity (i.e., theoretical knowledge requirements or mathematical computations necessary in normalization, preference weighting, or ranking), and Depth of Engagement in MCDA (i.e., form of preference elicitation and the number of opportunities for DM engagement, including feedback about model outcomes). The latter builds on the idea of interactivity in MCDA proposed by Marttunen et al. [171], but our work goes beyond to produce new insights on the similarities and differences of MCDA approaches and decision-making processes for group participatory hydropower decision support.

4.3. Methods

We review 25 studies that apply MCDA (or MCDA-like) approaches and/or DM group participation techniques (that could be coupled with MCDA) to water resource and/or hydropower decision-making processes. We recognize that many MCDA studies rely on equal or hypothetical DM preferences or solicit preferences from individuals, usually through a survey, as opposed to including a rich participatory in-person group process with diverse DMs. We also recognize that many studies that describe rich participatory in-person group processes do not use MCDA approaches. Therefore, we cast a wide net, trying to find studies within these two broad application categories. We do not restrict our literature review to a particular period as in the comprehensive review by Huang et al. [187]. We include studies older than 15 years if their methods were particularly detailed or informative in terms of DM engagement methods or modeling strategy. We note the type of model, type of participatory process, type of MCDA approach (section 4.2.), and whether participation or modeling was supported by visualization or software program.

Building on previous MCDA evaluative research (e.g., [171], [188], [191]), we assess these approaches for potential use in group participatory decision-making, which includes potentially conflicting management objectives, limited time and resources, and a need to make an educated decision about a dam with an accessible and understandable tool. We apply a 0-5 rating to each application study across two dimensions: Model Complexity (Figure 21), and Depth of DM Engagement [191] (Figure 22), based on the descriptions of model approaches and DM engagement processes in the articles. Then, we plot studies on a coordinate plane where the *X*-axis indicates model complexity and the *Y*-axis indicates *the* depth of DM engagement in the participatory process (section 4.5.). We use this assessment of individual application studies to describe trends across MCDA approaches and other participatory processes, leading toward a recommendation for group participatory hydropower dam decision support.

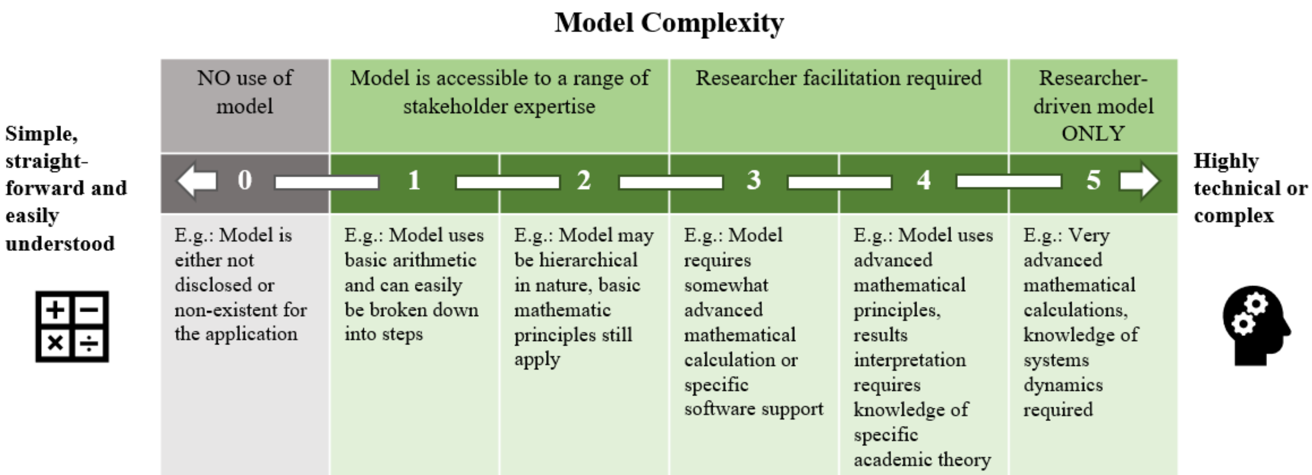


Figure 21. Spectrum for measurement of studies' Model Complexity.

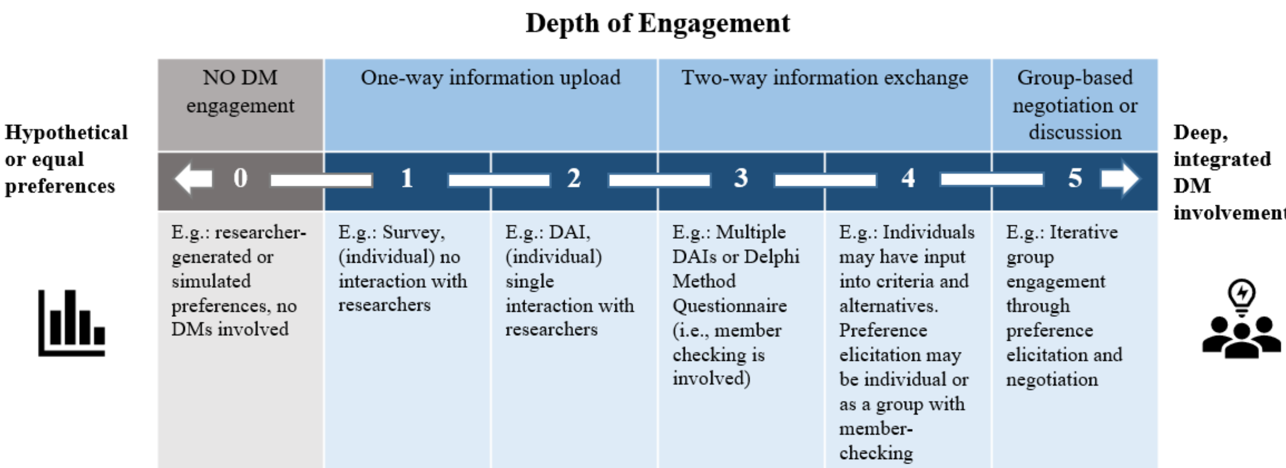


Figure 22. Spectrum for measurement of documented Depth of Engagement; i.e., stakeholder or DM involvement in MCDA.

For cases where the indicator does not apply, we assign a 0 rating (e.g., equal/hypothetical preferences or no model reported). Models requiring no researcher support or otherwise accessible to most DMs rate 1 or 2 on the Model Complexity scale. The more specific the software requirements, the more advanced the mathematical computations, the higher the rating (3 – 4). The distinguishing factor for a rating of 5 (as opposed to 4) is whether researcher facilitation is instrumental to proper use of the model, including optimization-based models that require advanced theoretical (e.g., systems dynamics) or mathematical training to run and interpret. For Depth of Engagement, surveys score at 1 on their own, Decision Analysis Interviews (DAIs) score at 2. Any member-checking activity (i.e., if researchers gather DM feedback on results) earns an additional point on the Depth of Engagement spectrum because it involves DMs at more than one stage in the process. Iterative meetings or multiple opportunities for participation that facilitate a two-way exchange of information garner higher ratings (3 or 4). True group-based negotiations or discussions achieve a rating of 5 because the engagement is social and interactive with opportunities to share and learn.

4.4. Review of Participatory Decision-Making Application Studies

Out of the 25 studies we reviewed (Table 25, grouped by model and then sorted chronologically), 21 describe a participatory process, 22 describe a decision support model (e.g., MCDA approach), and 5 describe decision outcomes (Appendix I has additional detail on specific Alternatives and Criteria considered in each study). Thirteen studies use a model with visualization (graphs, figures) to support participant understanding, and 13 use some form of decision support software. Eleven studies directly involve DMs (individually or as a group) in identifying (columns 9 – 10), and 10 studies involve DMs in rating (columns 11 – 12) Alternatives and/or Criteria. Eight studies involve DMs in *only* the rating activity (columns 11-12). Five studies do not engage DMs at all, while 4 studies do not disclose a specific model.

Table 25. Summary of MCDA studies reviewed

Author(s)	Year	Focus	Model	Participatory Process(es)	Vis.	Soft-ware	Stakeholder Involvement				2-Dimensional Classification	
							Dec. Alt.	Dec. Crit.	Rate Dec. Crit.	Rate Dec. Alt.	Model Complexity	Engagement Depth
Morimoto [203]	2013	M	WS	NS	Y	NS	N	N	N	N	1	0
Klein & Whalley [61]	2015	M	WS	NS	Y	NS	N	N	N	N	1	0
Mustajoki et al. [59]	2004	M, P	MAVT, Web-HIPRE	Decision Analysis Interview (DAI), SWING weighting (acronym never described)	Y	Y	N	N	I	I	2	3
Cai et al. [86]	2004	M, P	MAVT, Multi-objective algorithm (MOA)	Delphi Technique, Survey	NS	Y	G, I	G, I	G	G	5	5
Marttunen & Hämäläinen [60]	2008	M, P	MAVT, HIPRE 3+	DAI, SWING weighting	Y	Y	N	N	I	I	2	3
Trutnevyte et al. [87]	2012	M, P	MAVT	DAI, Scenario-Based Stakeholder Engagement (SBSE), Evolutionary Systems Design Framework (ESDF)	NS	NS	I	I	I	I	2	4
Bertsch & Fitchner [88]	2015	M, P	MAVT, Simulation-based Multi-Attribute Decision Analysis (SIMADA), PERSEUS-NET power systems analysis software	Survey	Y	Y	N	N	I	I	5	1

Table 25. (Continued)

Author(s)	Year	Focus	Model	Participatory Process(es)	Vis.	Soft-ware	Stakeholder Involvement				2-Dimensional Classification	
							Dec. Alt.	Dec. Crit.	Rate Dec. Crit.	Rate Dec. Alt.	Model Complexity	Engagement Depth
Kowalski et al. [89]	2009	D, M, P	PROMETHEE	DAI, SBSE, SIMOS (acronym never described), Silent Negotiation	Y	NS	G	G	G	G	3	4
Pictet & Bollinger [204]	2005	P	NS	Silent Negotiation	Y	NS	N	N	G	G	0	3
Marttunen & Hämäläinen [90]	1995	D, M, P	AHP, Simple Multi-Attribute Rating Technique (SMART) weighting, HIPRE 3+ computer program	DAI	Y	Y	N	N	I	I	3	3
Hämäläinen et al. [205]	2001	M, P	AHP, HIPRE (*Joint Gains* module)	DAI, ESDF	Y	Y	N	N	I	I	3	2
Antunes et al. [91]	2011	D, M, P	AHP, ExpertChoice	Social Multi-Criteria Evaluation (SMCE)	NS	Y	G	G	I, G	I, G	3	5
Stein [206]	2013	M	AHP, SuperDecisions	NS	Y	N	N	N	N	N	3	0
Kallis et al. [92]	2006	M, P	Novel Approach to Imprecise Assessment and Decision Environments (NAIADE)	Interview, DAI, Survey, NAIADE-based SMCE	Y	Y	G	G	NS	NS	3	4
Salgado et al. [93]	2009	M, P	NAIADE	SMCE	Y	Y	G	G	I, G	I, G	3	4
Simonovic & Bender [58]	1996	M, P	Collaborative Planning Support System (CPSS), SmartElements	DAI, SMCE	NS	Y	NS	G	I	NS	3	3

Table 25. (Continued)

Author(s)	Year	Focus	Model	Participatory Process(es)	Vis.	Soft-ware	Stakeholder Involvement				2-Dimensional Classification	
							Dec. Alt.	Dec. Crit.	Rate Dec. Crit.	Rate Dec. Alt.	Model Complexity	Engagement Depth
Van Eeten et al. [207]	2002	M, P	System Dynamics Simulation (SDS)	Gaming & Simulation, SBSE	Y	Y	NS	G	G	NS	5	5
Kallis et al. [92]	2006	M, P	SDS	Mediated Modeling (MM)-based SMCE	NS	Y	I	I	G	G	5	5
Manthrithilake & Liyanagama [208]	2012	D, M, P	SDS	Gaming & Simulation	Y	Y	G	NS	NS	G	5	5
Brown et al. [57]	2009	M	Interdisciplinary Dam Assessment Model (IDAM)	Delphi technique	Y	NS	N	N	N	N	2	0
Tullos et al. [56]	2010	M, P	IDAM	Survey, group workshop	Y	NS	N	N	I	I	2	3
Kallis et al. [92]	2006	M, P	NS	SBSE-based SMCE	NS	NS	N	N	G	G	0	5
Xenarios & Tziritis [201]	2007	P	NS	Focus Groups	NS	NS	G	G	N	N	0	5
Tompkins et al. [170]	2008	P	NS	SBSE, survey	NS	NS	I	I	G	G	0	5
Madani [209]	2011	M, P	NS	Gaming & Simulation	Y	NS	N	N	N	N	4	0

Table Abbreviations: Vis. = Visualization, D= Decision, M=Model, P=Process, NS=Not Specified, N=Neither, NA=Not Applicable, I=Individual, G=Group, Y=Yes

4.4.1. WS

Morimoto [203] and Klein and Whalley [61] both apply non-participatory WS to model-focused studies that include hydropower and use bar graphs to visualize ranked outcomes. Morimoto [203] assesses hydropower project development priority in Sri Lanka and compares the results to existing environmental impact assessments (EIAs) for different hydropower projects. The goal of Morimoto's study is site-specific project assessment, with Alternatives representing 22 small (less than 10 MW) Sri Lankan hydropower projects and rankings indicating development priority. Morimoto [203] creates an index for each Criterion category and a best-fit (x, y, z) plane to help visualize tradeoffs between Criteria in a closed-form solution. Unique to this study, weights are calculated as the inverse amount of electricity generated (i.e., scaled to eliminate project size impacts). The result is a ranked list of potential hydropower development projects in Sri Lanka, with an understanding of how weighted Criteria indices drive the ranking (e.g., the economic Criteria index has the greatest impact on Alternative ranking). Klein and Whalley [61] compare 13 U.S. electricity generation options and rank them based on a set of 8 Criteria and 10 hypothetical preference weighting scenarios. Hydropower ranks much lower (second-to-last, ahead of coal) than all other renewable electricity generation technologies in the equal preference scenario, but much higher (ranked one, two, or three, depending on the scenario) in the economic preference scenarios. The main contribution of this study is compiling and harmonizing data on multiple electricity options across many Criteria, so they can be compared and ranked in an MCDA, rather than developing a sophisticated model or eliciting DM preferences.

We rate these two studies at 1 for model complexity because WS requires basic arithmetic only, and is thus accessible to DMs with a range of expertise. Because it is so simple, WS can be easily calculated using Microsoft Excel or R software, both of which are widely accessible and support customizable visualization of results (e.g. ranked output bar graphs or rose plots comparing Criteria performance).

While this type of research benefits the scientific community and acts as a project scoping tool, the usefulness of WS in real-world applications depends on the preference elicitation methods and group participatory processes coupled with it. The studies reviewed here do not use a DM engagement process, so we rate them as 0 for Depth of Engagement.

4.4.2. MAVT

Two studies (Mustajoki et al. [195] and Marttunen and Hämäläinen [200]) explore individual participatory MCDA for Finland lake level regulation using individual DAIs (3-6 hours each [200]) and web-HIPRE (or HIPRE 3+ [200]) with a steering group of 20 ‘expert’ DMs, who discuss researcher-identified Criteria and Alternatives for decision matrix development. The web-HIPRE-supported DAIs help facilitate problem orientation, identify DM preferences through SWING weighting, and determine individual priorities [195]. HIPRE, a flexible, value tree-based decision support software for multiple MCDA approaches (e.g. AHP, MAVT), has multiple variations (e.g., HIPRE, HIPRE 3+, and web-HIPRE) and a selection of add-on modules (e.g., *Joint Gains*, hydrological modeling, impact assessment modeling) [200]. SWING weighting requires DMs to consider Criteria in a pairwise fashion, identifying a priority Criterion and assigning it 100 points before determining the relative weight of the other Criterion. Non-priority Criteria are allocated 0 – 99 points to indicate the relative preference of the DM (unless they are of equal priority, in which case the point allocation is 100 to both Criteria). It follows that the least-preferred Criterion in the set would be rated 0. The outcome is a direct DM preference rating and ranking of Criteria. Mustajoki et al. present researcher-assigned preference weights in web-HIPRE, as well as MCDA scores (calculation not disclosed) for different Alternatives (see Table I1) before SWING weighting. Marttunen and Hämäläinen normalize DM preference weights using division by sum after SWING weighting and then apply weights to a linear, additive value function (WS). Both studies use bar charts for visualization, with Marttunen and Hämäläinen including an interactive feature where DMs can try different weights and verify their choices, visualizing iterative results in real-time updated bar charts.

Mustajoki et al. report that DAIs improve DM understanding of the decision problem (assessment of this is unclear) [195]. The authors note that DAIs are individual rather than group processes, which they see as a shortcoming for general application. Both studies report optimism that their approach could be used in a group setting, but Marttunen and Hämäläinen acknowledge that time requirements for assigning preference weights may be prohibitive and neither studies offer specific ideas about group process mechanics. Both studies solicit participant feedback. Mustajoki et al. report 48% of participants agree (at least partly) that DM engagement was sufficient and 49% agree (at least partly) that study outcomes are beneficial/useful (compared to >80% for Marttunen and Hämäläinen). Marttunen and Hämäläinen report that their approach meets DM needs for participation and transparency and that all DMs consider SWING weighting to be suitable for comparing Criteria data that might otherwise be challenging to compare. These two studies rate 3 for Depth of Engagement due to steering group inputs (i.e., the authors used more than DAI), and 2 for Model Complexity, because it seems that weights are additive and linear as in WS; however, the application scores >1 because the authors perform a sensitivity analysis on DM preference weights (no result reported).

Cai et al. [86] combine multi-objective analysis (MOA) and group participatory MAVT to address regional water management conflicts (e.g., hydropower generation and irrigation) in North China. Researchers and 6 DMs (water managers and planners; no additional specificity about these groups) jointly identify Criteria. The authors apply a complete MAVT (facilitated using Delphi Technique) within each iteration of the MOA. Delphi is an iterative, expert-based elicitation technique, requiring a panel of DMs to fill out a questionnaire about Criteria preferences, after which a facilitator shares a summary of the responses back to the DM group for gut-checking or adjustment. In this application, the gut-checking portion of Delphi also includes a negotiation over preferred Alternatives. The MOA is a programming technique that uses a Tchebycheff algorithm (an evolutionary optimization approach) to iteratively sort/filter efficient policy options (Alternatives) generated by combining hydrologic, agricultural, and economic models. During this filtering process, a researcher-generated master list of Alternatives is narrowed into a smaller, more realistic list, informed by shared DM preferences. Cai et al. collect individual DM preference information (values indexed by m) to weight Criteria (i) for the first iteration of the MAVT-MOA. Afterward, it seems that the group discusses Alternatives for the MAVT. For the MAVT, Cai et al.

define a group decision support matrix (*S*) and single Criterion matrix, *E* (Equation 53). The MAVT looks a lot like WS (Eq. 63), because indeed it is very similar to WS, except where a group decision support matrix is created by multiplying the normalized Criteria matrix and a preference weight matrix that includes everyone's preference weight in the group for each Criterion. Then, this group decision support matrix is aggregated using an additive linear function (as in WS). While the MAVT recommends a 'first best' Alternative based on DM preferences, each MOA iteration requires the DMs to agree on a most preferred Alternative through consensus. After the most preferred Alternative is identified, it is fed back through the algorithm in the next iteration, a process that eventually results in an optimal solution.

$$S(i,m) = E(i,j) \cdot C(i,m) \qquad (53)$$

where i = Criterion, j = Alternative, C = preference weight matrix (normalized using Eq. 44-45) where Criterion weights are indexed by individual (m).

This approach seems to require considerable DM effort and time commitment. The researchers do not say how much time the entire process took, but we suspect several hours (if not multiple, intensive meetings) if a MAVT was performed at each MOA iteration as described. The iterative rounds of discussion may encourage shared learning, but Cai et al. [86] do not describe the participatory process in enough detail for us to draw more specific conclusions. This is primarily a methodology paper, describing specifically how the MOA approach can be coupled with MAVT to result in optimal management solutions for hydropower/irrigation, so there is no final decision to describe. Cai et al.'s application of the Delphi Technique earns a 5 for Depth of Engagement because although they use a questionnaire for preference elicitation in an initial MAVT, each iteration of the MOA is followed by a group negotiation or discussion to reach consensus for a new MAVT. The iterative Tchebycheff sorting algorithm earns the study a 5 for model complexity; because it requires specific knowledge of computational mathematical models, it is strictly a model used by researchers. Though the authors mention the use of a computational program, they neither identify the specific software used for the MOA-MAVT nor mention whether visualization was used to support DM understanding.

Trutnevyte et al. [87] incorporate preferences from 28 DMs in Urnäsch, Switzerland into scenarios for future local energy outcomes, ranking 20 energy mix scenarios for each of 6 shared Alternatives. Trutnevyte et al. first perform one-on-one discussions (i.e., DAIs) with DMs about broad management 'visions'. This approach is consistent with the ESDF [210], where models are evolved to meet DM needs for design. Researchers translate DAI themes into 1) a set of 6 Alternatives for local energy futures (Table I1), with 20 scenarios per Alternative (120 total), each comprised of 15 heat or electricity technologies; and 2) 7 Criteria. Criteria and Alternatives are ground-truthed in a second round of DAIs where DMs review and rank Alternatives directly, based first on pure preferences, then accompanied by Criteria data to see how their ranking changes with information. Preferences are treated linearly, as in WS (no other specifics about preferences are included). Trutnevyte et al. report that the vision-based approach opens and frames discussion about resource management, acting as a sorting procedure, not a choice procedure. Thus, the outcome of the MAVT (which seems to use WS) is the list of 6 ranked Alternatives ('visions'), though DM rankings are never reported. This approach develops robust possible future scenarios identified with DM input, grounding the discussions about possible energy futures in stakeholder-relevant issues [87]. We identify this study as an application of SBSE, a term defined by Tompkins et al. [170] as a stakeholder engagement-based natural resource management planning activity that uses hypothetical scenarios (these are defined consistent with decision alternatives in other MCDA studies) and deliberative discussion to identify decision criteria that are important to stakeholders. We adopt the term SBSE to describe other related engagement strategies (entitled 'scenario workshopping' [89] or 'stakeholder visioning' [87]) where DMs are engaged in building and considering specific, quantified, and realistic Alternatives ('visions'), potentially working together over time with researchers to either develop the model, give feedback about the Alternatives, or rank the Alternatives. Though the authors likely did not intend for their original definition to be used in this way, we assess that the other engagement strategies are similar enough to fall under the same heading. This iterative, two-way engagement earns them a 4 for Depth of Engagement, while the WS-MAVT earns a 2 for model complexity due to the added layer of complexity in scenario-based ‘visions’. Much like other studies reviewed here, Trutnevyte et al. use bar charts for visualization and do not report a specific software program used for the MAVT calculations.

Bertsch and Fichtner [88] demonstrate individual, survey-based participation in MAVT for power systems grid expansion planning with renewable energy sources in Germany. Their MAVT uses a MATLAB-run Simulation-based Multi-Attribute Decision Analysis (SIMADA) tool, coupled with electricity supply system software PERSEUS-NET, which simulates and optimizes electricity flows (including 260 large and 1600 small power plants, 1300 buses, and 1600 transmission lines) based on researcher inputs. PERSEUS-NET identifies Alternatives for grid expansion and other large energy infrastructure projects based on parameters set within existing policies for renewable electricity and then generates quantitative data for the MAVT researcher-generated Criteria matrix [88]. The authors surveyed 370 individual citizens and elicited Criteria preferences using the nine-point fundamental scale (e.g. AHP [183]). They use both interval-based (e.g., max/min survey responses normalized to a range of 0-1) and discrete (e.g., the mean survey response) Criteria preference information to generate weights. They perform sensitivity analyses on different weighting schemes using Monte Carlo simulation, which allows the researchers to better understand how preferences impact the final ranking, depicted visually as a scatter plot with error bars. The authors do report a full result (the top Alternative was renewable integration up to 90% of generation), but the main goal of the study seems to be methodological proof of concept, where citizen responses seem to serve as test data, for model validation. The authors use bar charts to visualize overall Alternative ranking and a series of line graphs to depict cumulative performance distributions for simulated Alternatives over time. This application rates 1 for Depth of Engagement because it relies on survey data collection for DM input. Due to the use of PERSEUS-NET in conjunction with the MAVT, what might have rated low due to additive linear preferences (i.e., WS) ends up rating 5 for Model Complexity.

All MAVT applications reviewed here use additive linear preference modeling (e.g., WS), but each is slightly more complex than standard WS due to hierarchical problem structuring (e.g., Criteria grouped into ‘objectives’, Alternatives grouped into scenario-based ‘visions’) and in some cases additional optimization software (e.g., MOA, PERSEUS-NET). Three out of the five MAVT applications reviewed here rely on custom or proprietary software programs (e.g. HIPRE, SIMADA) to perform the MAVT calculations. All studies used graphs to visualize results, except for Cai et al., who reported no visual output [86]. Of the 5 MAVT studies, 3 use DAI methods ([87], [195], [200]) and 2 use survey methods ([86], [88]) to elicit participant preferences for researcher-driven modeling. The main advantage of these MAVT applications to group participatory decision support research design is the iterative DM participation in modeling, incorporating feedback at multiple stages [87], [88], [200], which we did not see in the strict WS applications (these rely on simulated preferences).

4.4.3. PROMETHEE

In Styria, Austria, Kowalski et al. [89] use a group-based PROMETHEE II approach in considering renewable energy technology development Alternatives on a national and local scale in both individual stakeholder interviews and group workshops. The overall process is 1) stakeholder analysis to identify 25 DMs and stakeholder interests relevant to the problem; 2) first round of national and local workshops for stakeholders to help refine the relevant set of Criteria by considering up to 16 researcher-designated Alternatives (described as scenarios, making this SBSE), which were combinations of renewable heat and electricity; 3) researcher-developed final set of Criteria (Table I1); 5) second round of national and local workshops, where DMs use the SIMOS method (vague description) and 'silent negotiation' (groups rotated cards until they felt a compromise order was established, see [204]) to consider 5 Alternatives defined by technology-driven policies for renewable energy in Austria (Table I1). Final rankings showed DM preference for long-term investment technologies (e.g. solar PV, geothermal) and renewables composing local energy supply (e.g. heat pumps, solar thermal, solar PV). We rate this application at 3 for Model Complexity, because PROMETHEE requires advanced mathematical calculation by DMs (unlike WS), specific software, or researcher support in modeling. We rate Depth of Engagement at 4 because not only did direct DM input shape the set of Alternatives, but also the DMs were involved in the actual rating of those Alternatives in a group setting through iterative workshops at multiple levels (national and local). Kowalski et al. did not earn a 5 because we perceive silent negotiation to be somewhat limiting to rich discussion and social learning. This PROMETHEE application uses visualization (bar charts, to depict results, and movement of cards in the silent negotiation), but does not identify a specific software program.

Pictet and Bollinger [204] also use Silent Negotiation in a methodological study, not applied in any particular location. They do not link their methodology with any specific MCDA approach but recommend outranking approaches (e.g. PROMETHEE). Their procedure also uses cards, in this case focusing on Criteria rather than Alternatives (as in Kowalski et al.). Each DM in a group takes turns moving Criteria cards into a ranked order [204]. Cards may be moved after other DMs have placed them, and agreement is achieved when DMs no longer move cards or when a time limit is reached. After the ranking activity, DMs engage in discussions about the negotiation experience. While the technique is visual, the cards are text rather than image-based (as proposed), and the card placement within the set (e.g. first, second, third) indicates the group's relative ranking or priority over other Criteria. We rate silent negotiation at 0 for Model Complexity because no model is used, and at 3 for Depth of Engagement because it limits conversation and has the potential to cause frustration amongst DMs for whom discussion is an important aspect of learning. This rating is lower than Kowalski et al. [89] because Kowalski et al. involved DMs in Alternative development and implemented two rounds of two workshop levels (national and local).

4.4.4. AHP

Earlier work by Marttunen and Hämäläinen [90] focuses on a flood protection project in Finland, comparing individual-level AHP and SMART (a methodological offshoot of traditional AHP using a modified weighting technique) preference elicitation methods (both using HIPRE 3+ software) for 24 DMs (power company representatives; recreators; farmers; flood control officials; community mayors; environmental, agricultural, and fisheries authorities) considering researcher-identified Alternatives (e.g. dredging a river and tributary, or just the channel, the middle part of the river, the lower part of the river, etc.) and Criteria. Although the problem, Alternatives, and Criteria were presented to the DMs in a group setting (along with basic MCDA concepts), no discussion took place and the preference elicitation DAIs were completed individually (2 – 4 hours each). The final ranking (preferences aggregated using averaged DM values) was presented in a group seminar (bar graph visualization): (1) complete dredging project, (2) dredging middle part of the river, and (3) dredging the channel. The authors critique the fatiguing nature of AHP (which they call both "cumbersome" and "time-consuming"); however, they report that DMs gave negative feedback about the time and work required in the SMART method, too, and ultimately pass no judgment on methodological superiority. They evaluate DAI qualitatively (i.e. no rubric or grading system) for effectiveness using researcher observation (e.g. "overall the experiences were positive and encouraging"). This study earns a 3 for Depth of Engagement because DMs were interviewed for rating Criteria and Alternatives and also engaged as a group (but without interactive discussion).

In yet another Finland study, Hämäläinen et al. [205] examine the effectiveness of HIPRE (with Pareto optimal analysis module *Joint Gains*) for use with 34 students role-playing as DMs in DAIs. In the DAI, the student is interviewed by the researcher, who records 'DM' preferences in the software program and guides the interpretation of the results. Hämäläinen et al. ask students to play the roles of interest group DMs (e.g., farmers, power companies, summer residents) with differing priorities for lake level and flow release (the decision at hand). Hämäläinen and colleagues explore the use of an Evolutionary Systems Design Framework [210] (ESDF, where participatory model design is adjusted over time to meet DM needs). They use a form of MAVT where participants consider Criteria data ranges pairwise to elicit preference weights [205] before performing the MAVT calculations.

Alternatives are different water levels for a reservoir lake. Criteria are consistent with those previously described in similar Finland lake level studies (see [90],[59], [200]). Criteria weights are elicited using a visual, graphed approach. The user is asked about their preferences in one of two ways: (1) using interactive bar charts (e.g. toggle un-numbered slider bar right and left to see changes in the range of Alternative possibilities, "A" and "B", for a single Criterion indicated on the y-axis), (2) static bar charts where Alternatives are again labeled "A" and "B" (with some Criterion on the y-axis), and paired with another static set of bars labeled "A" and "B" with a different Criterion in the y-axis. In this second form of preference elicitation, one Alternative performs better on one Criterion and worse on the other. The user is asked to select "I prefer A to B" or vice versa to indicate a preference for one Alternative over another [205]. The preference elicitation approaches corresponded with slightly differing algorithmic approaches to finding a Pareto optimal Alternative because testing model mechanics is a goal of the study, though user preferences for criteria weight elicitation method are not reported. Individual decision outcomes are not reported because the purpose of the student experiments was to test the interface to see what process was most intuitive. Hämäläinen et al. report that their DAI approach and model interface meets DMs' preference for participation and addresses DM needs for transparency, so presumably, students were surveyed or interviewed after the preference elicitation activity, but no specific results are reported to support the researchers' assessments of how DM needs are met. Hämäläinen et al. conclude that the software would not be useful in the decision between Pareto-efficient Alternatives but may help move decision Alternatives toward more Pareto-efficient options; essentially, HIPRE may be more useful for Alternative development with DMs than with ultimate decision-making. This was a challenging model to rate because there was little information about specific calculations. We rate the application at 2 for Model Complexity, because value-tree based prioritizations of Pareto-optimal Alternatives are not simply WS-based but it is hard to judge what else might be happening here. We rate the application 2 for Depth of Participation because it was DAI-based with no clear indication that stakeholder inputs were iterative as in the other Finland lake level studies ([90],[59], [200]).

Unlike Marttunen and Hämäläinen [90], Antunes et al. apply the AHP using SMCE in a group participatory setting in a Portugal irrigation study [91]. DM groups include public irrigation, hydrological, agriculture, and development officials; agricultural associations and individual farmers; and experts in irrigation and agriculture (scientists). Antunes et al. describe AHP as not inherently designed for group participation, so they incorporate participation using SMCE principles. SMCE is a formal name for the integration of DM perspectives into model development using specific methods: institutional or stakeholder analysis, survey or DAI-based identification of Criteria and Alternatives, preference elicitation, and presentation of results back to DMs for feedback. Antunes et al. perform an institutional analysis, which includes DM identification and conceptually deconstructing management institutions using mixed qualitative methods (interviews, survey methods).

DMs assist in the problem framing phase of the research, where Criteria and Alternatives were collectively developed by participants and researchers together during two workshops [91]. Criteria were co-developed by DMs and researchers [91].

Antunes et al. then perform a series of DAIs (n=16) to elicit individual DM preferences through the pairwise comparison process. The actual AHP analysis was performed using ExpertChoice™ software, where individual preferences were aggregated using "non-compensatory mathematical algorithms" with no further detail. Finally, DMs reconvened in a group workshop setting for a presentation of the aggregated individual results and discussion of the ranked Alternatives, revising Alternatives as needed. The Alternatives were ranked as follows: (1) system modernization (e.g. new technology and management that meets diverse irrigator and agricultural user needs), (2) integrated water resources management (e.g. system-based rather than user-based water system management, incorporating new with old irrigation technologies, and (3) increasing communication between users and managers). The lowest two Alternatives were rehabilitation (reducing losses and costs, updating equipment and efficiency measures) and business-as-usual (do nothing), respectively. The authors report that ratings varied by DM type: public officials supported the rehabilitation Alternative; researchers chose integrated water resources management; farmers had no concrete group preference for Alternatives [91]. Antunes et al. also report using a sensitivity analysis function (i.e., playing with global Criteria weights to observe and measure changes in Alternative ranking) in ExpertChoice™, but do not say whether the different weights used were hypothetical or based on individual DM preferences. This approach contrasts with the seminar-style workshop used by Marttunen and Hämäläinen [90], which does not engage DMs in problem framing. Antunes et al.'s application rates a 5 because DMs were involved as a group in problem-structuring, then again individually in DAIs for preference elicitation, and once again as a group again in discussing and providing feedback about the aggregated results. The authors do not report if they used visualization support to aid DMs with their choices or in interpreting their results. This study rates at 3 for Model Complexity because of the specific software support used to perform the advanced calculations for analysis.

In a non-participatory AHP, Stein [206] considers renewable and non-renewable technologies for electricity generation in the U.S., like Klein and Whalley [61] (adding oil, not included in Klein and Whalley). Stein does not engage DMs in this research; rather, he simulates DM preferences using his expertise about U.S. stakeholders (utilities, elected officials, investors, technology suppliers, environmental groups, industry groups, government agencies, local communities, consumers, and businesses) preferences. The Criteria identified by Stein are sustainability-minded (as in Klein and Whalley [61]) (Table I1). Stein [206] used Super Decisions™ software to perform the actual AHP, which uses WS to weight preferences and calculate summed Criteria scores. Much like Klein and Whalley [61], Stein considers different simulated preference scenarios (e.g. equal weights) to capture different hypothetical stakeholder interests in the analysis [206]. In an equal weighting scenario, Stein finds that hydropower ranks third (of 9) overall for electricity technologies after wind and solar PV (unlike in Klein and Whalley's WS analysis, which ranks hydropower second-to-last under equal weighting). Hydropower ranks third (of 5) as an electricity technology for a "financial return" scenario, fourth (of nine) overall for a "community interest" preference, and first (again of 9) overall for a "production efficiency" scenario [206]. Klein and Whalley's WS analysis likewise puts hydropower in a top position when economic preferences define a scenario [61]. Like a majority of the previously described studies here, Stein uses bar graphs to depict the final ranking of Alternatives. Like the other AHP applications described above, this study rates 3 for Modeling Complexity due to the advanced nature of the mathematical computations in analysis and specific software used. We rate Stein et al.'s [206] application 0 for Depth of Engagement because, like Klein and Whalley [61] and Morimoto [203], he simulates stakeholder preferences in the study.

Benefits of a hybrid AHP/SMCE approach, according to Antunes et al., include: a better understanding of the Alternatives and complexities of the management decision (presumably because DMs are consulted in problem framing) and flexibility [91], referring to the process of presenting results back out the DMs for comment and adjustment. This is something that is not necessarily specific to AHP, but rather SMCE [58], [91]–[93]. The major drawback to the use of AHP, as mentioned by Marttunen and Hämäläinen, is the potential for DM fatigue [90]. We rate all AHP applications discussed here 3 for modeling complexity because the model is not overly complicated in and of itself if the number of Criteria and Alternatives are low, but there is potential for complexity with additional Criteria. Also, 2 of 3 AHP studies reviewed here use non-open source software to perform calculations (e.g., SuperDecisions™ and ExpertChoice™). We rate the depth of engagement differently for each study.

4.4.5. NAIADE

Recall that NAIADE is the name of both an approach and software specifically designed to support its implementation. The NAIADE approach is designed for group participation (unlike other MCDA approaches), incorporating the conflict analysis process through the 'equity matrix' and 'similarity matrix' (see section 4.2.). Kallis et al. [92] use NAIADE, which they describe as a type of SMCE, in a group participatory workshop for water management in coastal Spain, as a part of a comparative case study (other cases discussed in section 4.4.6.4). Like Antunes et al. (who also use SMCE), Kallis et al. first perform an institutional analysis (problem scoping), followed by in-depth interviews with 16 individual DMs (government authorities, businesses, NGOs) to identify Alternatives for use in the NAIADE [92]. Paneque Salgado et al. [93], publishing a few years later but part of the Kallis et al. research team, offer some additional details in Kallis et al.'s account of the Spain case study. The study used a survey (N=425) to elicit Criteria preference information [93], but it is unclear how the results were used in the NAIADE (i.e., we do not know if the surveys were used to compare against group preference values or aggregated to be used in another way). Kallis et al. perform the NAIADE with the DMs individually (DAI) and return to the DMs in a group setting (much like Antunes et al.) to share and ground truth the ranked results. At this stage, DM participants added an Alternative entitled "reforestation of the basin" (reported as the preferred Alternative) and parsed out one Alternative into three distinct Alternatives (included in the final list, Table I1) [92]. Kallis et al. are vague about their specific implementation of NAIADE, except that the approach was analyst-driven (compared similar studies, see sections 4.4.6.2, 4.4.6.4), limiting the group deliberative aspect [92]. We piece together this understanding of the coastal Spain NAIADE and SMCE application using studies by Kallis et al. [92] and Paneque Salgado et al. [93] because both are unclear on various aspects of the case study.

Like the AHP approach described by Antunes et al. [91], DMs are involved in two phases for this NAIADE application because the authors use SMCE, and in addition to the institutional analysis, SMCE calls for DAIs and group discussion over the final set of Alternatives, so we rate the depth of engagement 4 for both studies. Unlike WS, MAUT/MAVT, PROMETHEE, and AHP, it appears that there is a dedicated software program for the implementation of NAIADE which includes graphics to enhance understanding of group linkages (e.g. response similarity) [93]. We rate model complexity 3 for this study because it is somewhat more complicated than WS, and, like PROMETHEE, requires familiarity with advanced mathematical computation and specific software program (NAIADE, which has some graphic charts for user interpretation).

4.4.6. Non-MCDA Approaches

While most participatory decision-making processes we review use modeling, those that do not use modeling appear to be compatible with MCDA as a form of decision support. We break down our discussion of non-MCDA approaches into model sub-categories: CPSS (section 4.4.6.1), SDS (section 4.4.6.2), IDAM (section 4.4.6.3), and Other (section 4.4.6.4). Studies are listed chronologically within each sub-category, as above.

4.4.6.1. CPSS

Simonovic and Bender [58] develop CPSS software to help DMs reach consensus about a proposed hydropower project in Northern Manitoba, Canada. Though not MCDA by name, the CPSS framework is structured similarly. Likewise, the process of engaging stakeholders in model development seems to be a modified version of SMCE, with a focus on individual, rather than group, engagement. Researchers first develop Criteria cooperatively with DMs unconstrained by consideration of Alternatives. DMs are asked to select “core” Criteria (referred to as “grounded facts”) from a master list developed by researchers, winnowing into a smaller shared “knowledge base” for preference elicitation. DMs use SmartElements™ for individual preference elicitation using a DAI-like process. DMs are first presented with the knowledge base list of Criteria and then asked to identify a list of top-priority Criteria, adding them to a new ‘personal’ list. This personal Criteria list is shown adjacent to a dynamic ‘global’ Criteria list, collected from all DMs interacting with the model. The global Criteria are the ones used by the software program, determined by a researcher-defined set of Boolean rules (i.e., if this, then that). After preference elicitation, SmartElements^{TM} then assembles the 'global' Criteria, which define the various realistic Alternatives (unspecified). DMs presumably discuss the results in a group setting afterward, but it is not reported. The study described by Simonovic and Bender was a test run of the CPSS using 2 representative DMs, a dam developer and an environmental regulator [58]. This particular approach was developed for application with a hydropower development project but the *final* set of Criteria and Alternatives were never identified. Much like other more model-based studies reviewed here ([86], [88], [90], [204]), no actual decision was made.

The authors clarify, stepwise, how the DM engagement process takes place better than some of the other well-documented engagement-based studies we have reviewed ([89], [91], [92]), but there are still gaps in reporting. While Boolean rules require some threshold (e.g., number of DMs selecting the same Criterion) to include Criteria on the global list, threshold values are not disclosed. And, it is unclear whether some base set of Criteria relevant to the decision problem needs to be considered regardless of DM priorities (e.g., legal minimum flows). Likewise, the set of rules seems to translate to preference weights, but the mechanism is not identified nor compensation between criteria discussed. The timing of the preference elicitation is likewise unclear; it seems that multiple DMs could use the program individually and simultaneously if the program were connected to a network or the internet. The authors do not state whether they used a visualization of any kind. We rate Simonovic and Bender's [58] CPSS approach 3 for model complexity because while the preference elicitation process is predominantly verbal and list-based, with direct Criteria prioritizations (DMs rank them), Boolean rules require some understanding of advanced mathematical computation (i.e., it is unlikely that a DM could use this without researcher support). In this proof-of-concept study, we rate CPSS at 3 for Depth of Engagement because although the final Criteria list simultaneously developed and directly rated by DMs, there is a lack of DM participation in problem structuring. The model seems to use only researcher-driven identification of Criteria and Alternatives.

4.4.6.2. SDS

Van Eeten et al. [207] use a hydrologic system dynamics simulation (SDS) model in group-based river resource management decisions in the Everglades, Columbia River Basin, and the San Francisco Bay-Delta in the U.S. The SDS model consists of time series data for specific hydrological Criteria, each measured by percentage time exceedance for a given ‘normal’ data range. Criteria within the river system are depicted using time series graphs, percept exceedance graphs, and a color-coded table (so there is a visual element to this approach). Preference elicitation is achieved through scenario-based participatory gaming, which we are categorizing as SBSE (for consistency), where a DM group is challenged to allocate water month-by-month to meet basic water supply needs, as well as long-run management goals beyond water allocation in a series of hypothetical scenarios [207]. The SDS model is responsive to different DM inputs, so the group may toggle between potential inputs and outcomes to reach a consensus. The process is described as intensive (week-long immersion in scenarios, modeling, deliberative discussions) and iterative, with model-sharing, discussion of potential outcomes, model revisions, and policy development. Alternatives (never specifically identified) seem to be policy-based, but the final decision is never mentioned. Though the authors report little methodological detail, it seems that the study aims to explore the use of SDS model with the gaming process, rather than the decision itself. We rate this application at 5 for Depth of Engagement, because DMs were engaged in an iterative group discussion about policy-based Alternatives. Participants were involved in the development of the final model, as well as in the ultimate decision process. We rate this application at 5 for Model Complexity, because SDS requires dynamic, system-based mathematical calculations and specific software, though no program was mentioned.

In addition to their NAIADE study, Kallis et al. use other group participatory methods for decision-making about water resources planning [92], including an MM-based SBSE of water planning in Baixo Guadiana, Portugal. MM refers to the iterative nature of facilitated modeling and discussion with DMs. Kallis et al.’s MM process begins like any SMCE (and like their NAIADE study), with a formal stakeholder analysis. After stakeholders were identified, Kallis et al. performed introductory interviews (DAIs, no specific number given) to identify issues in water resource management. Based on the interviews, researchers put together a preliminary SDS model, using researcher and DM-defined Criteria. Then, DMs (e.g. water authorities, municipal authorities, regional directorates, developers, environmental groups, researchers, and homeowners) help identify qualitative cause-and-effect relationships and provide quantitative information to help analysts refine the SDS model over a series of 3 intensive group-based modeling workshops (n=57, n=27, n=20, respectively). The authors do not offer a complete list of Criteria or Alternatives, but we do know they were both discussed by DMs during MM. Kallis et al. followed up the MM workshop series with individual questionnaires, where DMs were asked to assess the process, but again no specific number of survey responses is reported. No final decision was made as a part of this process.

Kallis et al. [92] provide a general assessment of the participant experience but are cursory in their evaluation. The lack of detail in the description of this study is both striking and confusing: the authors only briefly mention the role of the SDS model in DM assessment of tradeoffs (presumably as a learning tool) and do not refer to specific DM feedback or interview quotations to support their assessment that the transparency of the modeling process helped quell DM concerns about technical complexity. Though the authors call the modeling software ‘visually oriented’, specific visualization examples are not provided, and the software is never named. We rate this application at 5 for Depth of Engagement, because despite the limited nature of the reporting, the group discussion seems to have been both intensive and iterative, We rate the application 5 for Model Complexity (again, despite limited reporting) because SDS requires advanced mathematical computations.

Like van Eeten et al. [207] and Kallis et al. [92], Manthrithilake and Liyanagama [208] use an SDS model (using Acres Reservoir Simulation software) paired with a participatory process for planning agreement amongst water authorities over water allocation and basin use for hydropower, drinking water, and irrigation in Sri Lanka. Manthrithilake and Liyanagama’s is the only study we review that uses the SDS for real decision-making, where hydrologic model flows inform dynamic, real-world regulation. Flows are simulated and balanced within the model using technical indicators (inflow, outflow, losses) for a system of penalties and allocations based on an informal, government-issued ranked list of water allocative priorities (Alternatives). Water use priorities often conflict during the dry season (minimum flow), which is the motivation for DM engagement in the decision process, so the expert Water Management Panel (a collection of government authorities, electricity board members, irrigation department representatives, farmers, and drinking water supply officials) devises a plan for allocations, identifies a technically viable Alternative based on SDS results, and implements the plan [208]. The plan is revised as needed.

Though the authors report that the Acres Reservoir Simulation has been little used outside of Sri Lanka [208], they suggest that its potential is nonetheless robust, due to its built-in capability to generate technically viable Alternatives and its proven usefulness (the model has been used to support planning for many years now). The Criteria built into the model or discussed by DMs is unclear in this study, but the iterative input/modeling/revision process appears flexible enough to be applied to other resource management issues outside of water allocation. The focus of the paper is the SDS model, so Manthrithilake and Liyanagama offer few participatory process details (how many iterations, how much time between, how many individuals, whether or not discussion is facilitated by an outside party) [208]. Despite this, we rate this application at 5 for Depth of Engagement, because of the multiple opportunities for DM participation in iterative revision of the model (Criteria values, usually), over time. SDS requires an understanding of the entire water system, as well as familiarity with simulation and time-series data, so we rate this application at 5 for Model Complexity.

SDS with gaming is different from traditional MCDA because it takes a dynamic approach (and, as we have seen in this review, MCDA is usually static or site-specific) both to modeling and participation (decision makers are involved at multiple points in time). All SDS model approaches described here ([92],[207],[208]) are rated identically for Model Complexity and Depth of Engagement. Despite the complexity of SDS modeling, van Eeten et al report exposure of participants to different or unfamiliar regulatory systems and management strategies as a positive outcome [207]. Across the board, iterative group-based discussion and modeling with SDS appear to be time-intensive. Kallis et al. mention that participation drop-off was a significant problem for their MM workshops; the number of participants dwindled from 57 to 20 over a series of only 3 meetings, and 'agenda constraints' was the reason offered by a few participants unable to attend [92].

4.4.6.3. IDAM

Brown et al. develop the IDAM tool in a non-participatory, theoretical (no specific location is mentioned), model-only study. IDAM is a form of dam decision support to aid DMs in comparing Criteria and identifying preference weights using segmented rose plot diagrams [57]. The IDAM tool focuses on 27 Criteria grouped into themes (geopolitical, socioeconomic, biophysical) that make up portions of a circular 'pie'. Following this metaphor, you might imagine a circle divided (1) evenly into three theme 'portions', (2) sub-divided by degrees into Criterion 'slices' (13.3°), then divided (3) by degrees into 5 (thin) objective 'pieces' (2.7°), and (4) radially into 5 subjective 'bites' (Figure 23). The objective scale is tailored to specific Criteria (so the DM would consider 27 of these), while the subjective scale is more generic, asking for DM's judgment of relative impact of the Alternative on specific Criteria. A benefit-cost analysis process uses two identical pies, one represents costs, while the other represents benefits.

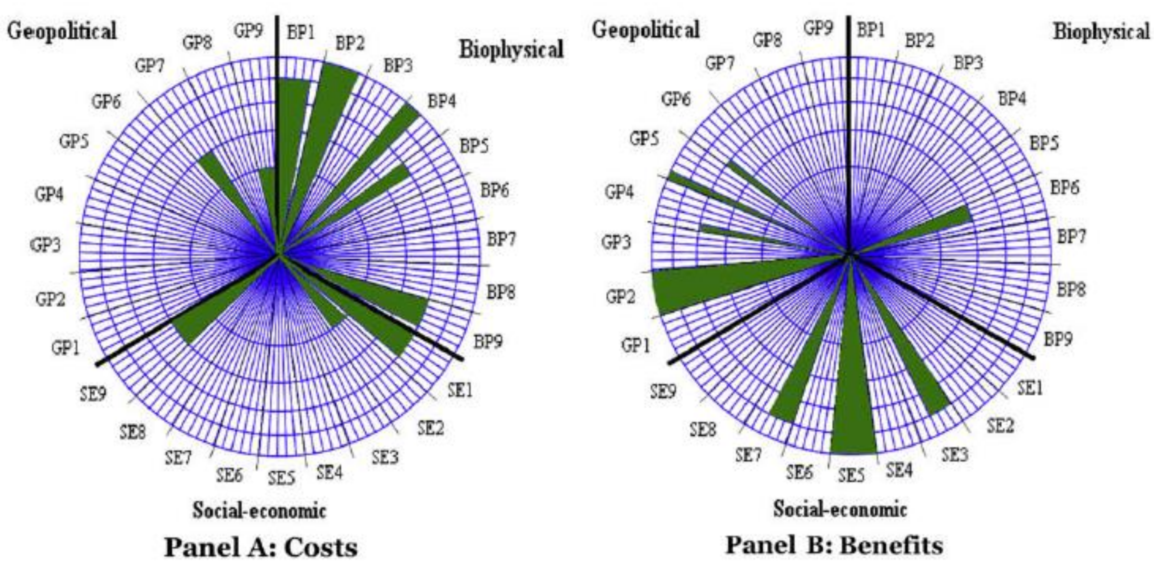


Figure 23. IDAM benefit and cost comparison of geopolitical (GP) and biophysical (BP) decision criteria division into objective 'pieces' and subjective 'bites'. Source: Brown et al. *[57]*.

Although IDAM is framed as a cost-benefit analysis tool, much like MCDA, it pushes beyond standard cost-benefit analysis by combining qualitative ratings (e.g. Likert scale) and quantitative measures (economic & biophysical data) while visually ‘normalizing’ across the Criteria (‘slices’ of the ‘pie’) using DM preferences [57]. Brown and colleagues [57] recommend the use of the Delphi Technique to facilitate preference weight elicitation using IDAM, anticipating that the familiar, structured, and expert-based participatory technique may reduce user confusion and streamline participation (refer to our description of Cai et al. [86] for additional detail on this method). The Brown et al. [57] application does not engage DMs so we rate it at 0 for Depth of Engagement. We rate it at 2 for Model Complexity because though simple (and comparable to WS), the visual breakdown of Criteria rating is not immediately obvious and as an approach would require some work to integrate into an MCDA method to achieve a ranked outcome.

The IDAM tool is tested in a proof-of-concept model and process-focused study by Tullos et al., using participatory workshops and survey methods [56], a slight deviation from Brown et al.’s [57] Delphi recommendation. In three group workshops (not iterative, each workshop engaged a different sub-group of DMs), Tullos et al. introduce a total of 15 DMs representing ‘expert’ groups (e.g., academia, NGOs, hydropower companies, public officials) to the IDAM and hold an open discussion about dam impacts [56]. DMs are asked to consider their perception of Criterion salience (i.e., importance, a subjective scale: -4 = extreme negative to +4 = extreme positive, where 0 = no importance) for dams in general. The DMs are then introduced to two simulated hydropower development scenarios (a large main-stem dam, and multiple smaller tributary dams) in Yunnan Province, China as context, and are surveyed about the magnitude of impact (an objective scale) for each Criterion. According to Tullos et al., the IDAM tool has the advantage of transparency, because DMs get a visual of the process. Although the model was tested with DMs individually via survey, it seems that the process and model were the focus of the study because no decision was documented. No software is documented as a part of this study, either. We rate Tullos et al.’s [56] application of IDAM 3 for Depth of Engagement because they combine individual survey data collection with a group workshop. It seems that the focus of the workshop was an introduction to dam decision-making, and not discussion, so we do not rate the application at 4. As with Brown et al. [57] (and for the same reasons), we rate this application of IDAM 2 for model complexity. The IDAM tool shows promise for usefulness for dam decision-making because of its use of a visual for eliciting preference weights, which provides users with a tradeoff-based understanding of their priorities. However, we anticipate that IDAM would require considerable explanation before use (a drawback). Tullos et al. [56] report that IDAM may be combined with participatory techniques other than the Delphi Technique, and we suspect that IDAM may be paired with many other non-MCDA approaches (e.g., those in section 4.4.6.4).

4.4.6.4. Other

Kallis et al. [92] use a group SBSE-based SMCE (they refer to this as ‘scenario workshopping’, or SW) for freshwater allocation conflicts in Naxos, Greece in addition to their two previous studies (NAIADE, and MM with SDS). The SBSE-based SMCE study takes place in Naxos, Greece [92], where Kallis et al. perform formal stakeholder analyses, interviewing water managers and identifying DMs to invite to the workshop. The authors then draft four preliminary Alternatives for participant consideration. A total of 36 DMs (agricultural policymakers, tourism policymakers, experts, NGOs, citizens) attended a two-day group workshop. A professional, third-party facilitator guided DMs in developing a group vision statement to guide deliberation over the ultimate management decision, then worked backward to strategize about actions and voluntary partnerships that would lead toward the management goal. DMs discussed researcher-identified Alternatives first, and then (in small groups) came up with other possible Alternatives. Finally, they voted on the full set. Each participant was given 5 votes to allocate according to their preference. Education programs rated highest, followed by natural infrastructure for water conservation, and finally investment toward laboratory testing for water quality [92]. After the workshop, the researchers assessed the participant experience using a follow-up questionnaire. Although the researchers report that SBSE facilitates discussion between participants, they observe that the workshop did not lead to real and lasting partnerships or an official decision by policymakers, noting that discussion also bred disagreement (as in the MM and NAIADE studies, no detail on the authors’ process for evaluation). Though the authors mention participant satisfaction with discussion, they also mention participant frustration over the process of voting with limited information and the general lack of detail in describing the Alternatives [92]. No final decision was reported.

This application rates at 5 for Depth of Engagement, because DMs were involved in both the selection of Criteria and Alternatives. Kallis et al. [92] do not mention a specific model, so Model Complexity rates at 0.

Xenarios and Tziritis [201] adopt focus group and content analysis techniques for eliciting group DM preferences for use in an MCDA (the approach was never defined, but the context indicates MAUT or MAVT) on watershed decisions in Axios, Greece. The authors begin with stakeholder analysis methodology (consistent with SMCE methods) to identify the following DMs: farmer, mussel farmer, industry, water supplier, hunter, cattle breeder, environmental group, and mayors. Then, in a focus group setting (e.g., a collection of hand-picked participants take part in a discussion facilitated by a professional third-party and observed by researchers), DMs are asked to consider a set of pre-determined expert-identified Criteria and Alternatives for a hypothetical decision about real water resources. DMs select and adjust the set of criteria during 4 iterations of these 2-hour facilitated discussions (with 8 – 12 DMs each). The focus group discussions are the preference elicitation process.

The authors then use content analysis (thematic text coding) to identify shared preferences and the influence DMs have on one another. Focus group discussions were recorded, transcribed, and coded for preference indicators: relative frequency of word mention, non-motivated content, and tension. These preference indicators are aggregated somehow (mechanism not reported) to calculate the decimal scaling for Criteria weight values. The authors also code Criteria formulation based on participant type: Criteria established by experts (before the focus groups) and Criteria suggested by DMs [201]. Like Pictet and Bollinger [204], Xenarios and Tziritis [201] focus solely on the participatory process aspect of the research. The focus groups and content analysis are used as a means for identifying the final Criteria and preference weights to be used in MCDA. This study provides the most thorough example of process documentation that we have seen so far in this literature review. The derived preference weights are unclear, as are the actual management Alternatives considered for Axios. No visualization or specific software is mentioned in this study. Though the authors mention that their focus group approach was intended to be paired with MCDA, Xenarios and Tziritis [201] neither select any one specific type of MCDA, nor do they describe the model used outside of its Criteria. As such, we rate the application at 0 for Model Complexity. We rate the application at 5 for Depth of Engagement due to the group discussion-based preference elicitation approach and the authors' emphasis on integrating DM-generated Criteria (14 of 39 total Criteria were developed this way) into the decision matrix.

Tompkins and colleagues [170] used a group SBSE to engage United Kingdom DMs in planning for realistic coastal climate change scenarios in Orkney and Christchurch, where the goal was to initiate a process for decision-making under uncertainty. The authors first identify local DMs in a formal stakeholder analysis (using document review, key informant snowball methods including discussions with local municipal boards and councils). Christchurch DMs (n=18) included coastal authorities, spatial planners, conservationists, environmental educators, homeowners, and recreators. Orkney DMs (n=13) included transportation authorities, public administrators, local developers, businesses, and environmental and coastal scientists. Tompkins et al. then perform problem scoping using local climate change data. In this problem-scoping step, the authors develop hypothetical but realistic climate change scenarios based on existing typologies (e.g. coastal flooding, erosion due to rising sea levels, damage to coastal infrastructure) modified to the site, including reactive (i.e., mitigation only, no preventative actions were taken) and anticipative (i.e., planning, includes protective measures) local actions. DMs were invited to a group workshop to deliberate over climate change planning approaches in the researcher-identified future scenarios. The focus of the workshops (one each at Christchurch and Orkney) was to identify group DM priorities directly through a ranking of issues (1= top priority to 3=lowest priority), followed by voting (allocation of 10 votes each amongst the top 3 issues, presumably to get at cardinality, as in SWING weighting for MAVT [195], [200]) [170]. Like Kallis et al. [92], Mustajoki et al. [195], and Marttunen and Hamalainen [200], Tompkins et al. [170] use pre- and post-workshop questionnaires so DMs could again rank the issues, concerns, risks, and ask key questions in climate change planning (no further detail provided). The result of this SBSE is a deliberated and consensus-based planning approach (as opposed to a ranked outcome, as with MCDA) preferred by a group of DMs who may use it to plan for future contingencies under climate change uncertainty [170]. The approaches were defined loosely as localized or centralized, as well as anticipatory or reactive. For instance, Christchurch Bay DMs were more supportive of centralized decision-making, while Orkney Islands DMs were more pro-local. The authors report general support anticipatory decision-making in both cases.

Unlike the MCDA-based applications of SBSE ([87], [92], [211]), Tompkins et al.'s SBSE study emphasizes general planning strategies based on general climate change impacts expected geographically and the locally relevant, social coastal management issues that concern DMs. Though the focus of the workshop was group decision-making, the pre- and post-workshop surveys allow DMs to individually rank the issues, concerns, risks, and key questions they have about climate change planning as well. DMs were asked open-ended questions such as: "Should we act in anticipation of impacts? Always? What happens if we take measures which may turn out to be unnecessary?" [170]. The group vs. individual preference comparison allows the authors to isolate factors influencing individual DM management preferences: local context; availability of planning information; and perceived access to resources, individual vulnerability, and control over mitigation efforts. Tompkins et al. do not report visualization or software of any kind. We rate this study at 0 for Model Complexity because no model was used, and 5 for Depth of Engagement because DMs were involved as a group in deliberative discussion.

Madani [209] proposes a theoretically (so, not yet participatory) cooperative, game theory-based approach that mimics the U.S. Federal Energy Regulatory Commission (FERC) relicensing process (which determines whether a non-federally owned hydropower project is approved for operation). In a theoretical study (based on process *and* model, in this case), Madani employs Nash (Pareto optimal outcome for a game where optimization requires DM cooperation) and Nash-Harsanyi (where multiple games lead to strategic individual losses in service to long-term group gains through cooperation) bargaining strategies to explore negotiations between non-federal dam owners and environmental groups over hydro operations [209]. Madani's game-theoretic approach is notably unique because it relies so heavily on economic theory (though perhaps there are parallels to be drawn between this approach and expected utility assessment for MAUT). While Madani's approach engages no actual dam owners or environmental groups and reframes the FERC process as user-based (rather than project-based) and cooperative (e.g. coming up with strategic, novel, and in the long run, mutually beneficial license agreements for joint gains). Madani reports no software, but this approach could potentially be linked with a limited-scope SDS (due to its use of time-series data). Madani reports bar chart visuals to show negotiated outcomes over time. This approach may be useful for groups seeking insights about what approach to negotiation might be most successful based on their desired outcomes for intervening in relicensing. Madani's [209] game theoretic approach has a clear contextual advantage over all studies mentioned here because it is the most specific to our own dam decision making context: FERC-licensed hydropower dams in New England. The actual model that Madani suggests is perhaps better suited to the realm of learning exercise because it requires a deep understanding of economic risk behavior, as well as mathematical computation. The model itself is not something that DMs could use without researcher or facilitator support. For these reasons, the application is rated at 4 for model complexity. Though it serves as a mathematical representation of real-world decision making about dams, the application negotiation described by Madani is purely hypothetical. With a hypothetical negotiation and no specific process structure or facilitation strategy referenced as a support for participants in the game, we rate depth of engagement 0 for this application.

The non-MCDA SBSE approaches (e.g., Kallis et al. [92] and Tompkins et al. [170]) appear to be well-suited to integrate with MCDA due to general process similarities; namely, DM deliberation over Criteria within realistic Alternatives to determine a priority outcome (though in all cases, the actual outcome is not stated). SBSE *can* generate a prioritized set (see for example [87], [89], [170]) of Alternatives, policies, or planning approaches (note: this is not required for SBSE, and the non-MCDA applications do not use mathematical ranking). It is also important to note that while these applications did not result in actual decision outcomes, both sets of authors report that their workshop was positioned to support local planning processes (under climate change or limited water availability). We rate both studies similarly for both Model Complexity and Depth of Engagement. Madani's study is, of course, an outlier.

4.4.7. Two-Dimensional Rating

We now plot each study on a 2-dimensional coordinate plane, according to their ratings for Model Complexity and Depth of Engagement (Table 25). Studies using SDS were, in general, more complex than other decision making approaches (e.g., [92], [207], [208]), but they were also more engaging. On the other end of the Modeling Complexity spectrum (lower left-hand corner of Figure 24) lie both applications of WS (e.g., [61], [203]), where the models are simple and straightforward, implemented as a demonstration of MCDA for sustainability assessment. Several studies we reviewed, including both WS applications, did not use real DM preference weights (e.g., [57], [61], [203], [206], [209]), so the applications sit on the *Y*-axis. Directly along the *X*-axis are four strategies that engaged DMs in a participatory way, but did not mention a specific model (see [92], [170], [201], [204]).). Populating the center of the coordinate plane, i.e. (2,2) to (3,4), are: an application study of AHP with DAI ([90], [205]), IDAM application with Delphi Technique ([56]), MAVT approaches with enhanced DM involvement (see [195], [200]), PROMETHEE (see [89]), CPSS (see [58]), and NAIADE (see [92], [93]).

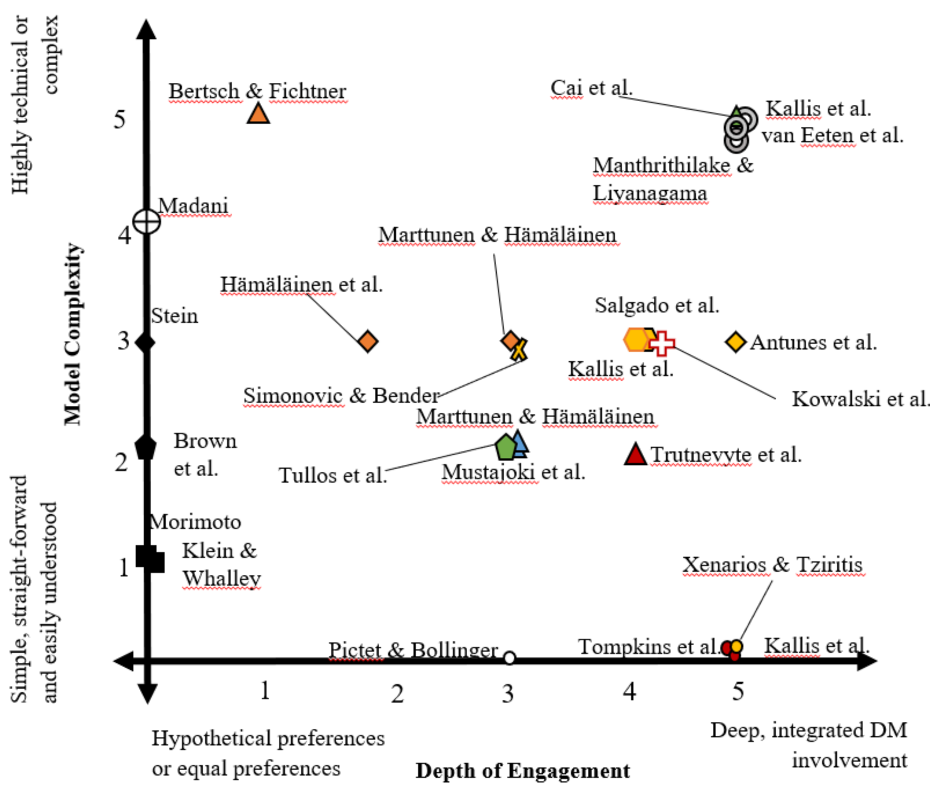


Figure 24. Two-dimensional assessment of application studies. Shapes indicate general model type: triangle = MAVT, square = WS, diamond = AHP, cross = PROMETHEE, open circle = SDS, x = CPSS, hexagon = NAIADE, pentagon = IDAM, closed circle = participatory process only. Colors represent participatory process: black = model *only*, orange = DAI or survey *only*, green = Delphi Technique, blue = SWING or SMART weighting exercise, gray = gaming & simulation or MM, yellow = SMCE, white = 'silent negotiation', red = SBSE or focus group. White circle with cross labeled "Madani" uses game theory modeling.

In the 25 studies we review, 13 studies rate 3 or lower on the depth of engagement scale, which means they exclude group reporting and feedback or discussion from their participatory process or otherwise focus on individuals. A heroic few studies (4) attempt to balance deep engagement with complex modeling (e.g., [30], [55], [63]). For example, Cai et al. [86] pair their complex MOA with an engaging approach that circles back to the group of DMs to incorporate shared preferences at each iteration of the model. Bertsch and Fichtner [88] do the opposite, balancing their complex PERSEUS-NET model with survey-based engagement. We find the lowest complexity in WS and MAVT model applications and the highest complexity in applications that couple MCDA with additional simulation (e.g., MAVT with MOA [86], MAVT with PERSEUS-NET [88], or SDS [92], [207], [208]). We also find that approaches with the greatest depth of engagement (4 – 5) are Delphi Technique [86], Focus Groups [201], SBSE ([87], [89], [92], [170], [207]), and SMCE [58], [91]–[93]. Processes with the least depth of engagement simulate DM preferences ([61], [203], [206], [209]) or strictly use survey ([88]) for preference elicitation (rating 0 - 1). Nine studies rest in the middle of both spectra, balancing both depth of engagement and model complexity, but our ability to draw conclusions about these studies' placement is limited by the lack of specific information on both models and participatory processes. Importantly, our analysis highlights an unexpected gap: comparatively, we find no instances of simple models (Model Complexity =1) used for deep engagement with DMs.

4.5. Discussion

This paper has presented a targeted review of the literature intended to identify the MCDA model/process with the most promise for group hydropower dam decision support. Our goal was to identify a model to support DM groups without the need for a researcher, a simple and straightforward model capable of accommodating group participation. Based on our assessment, WS is the most appropriate MCDA approach for our purposes. While the strictly WS studies we review here use simulated preferences [61], [203], the MAVT studies that use WS do integrate individual (see [195], [205]) and group (see [86], [87], [200]) stakeholder preferences in a participatory way. The WS (or MAVT-WS) approach is simple, rating 1-2 on the model complexity scale in all applications (see [61], [87], [195], [200], [203]). Other

MCDA (MAUT, PROMETHEE, AHP, NAIADE) or MCDA-adjacent models (SDS, IDAM, CPSS) would all require researcher support or in-depth training materials (which translates to time spent) for users. WS is also paired with diverse participatory approaches for preference elicitation including SBSE (see [87]), DAI (see [87], [195], [200], [205]), and SWING weighting (see [195], [200]). The simplicity and flexibility of WS are an advantage in hydropower dam decision making, where every decision is nuanced and site-specific, and where different groups of DMs might be involved at each site. Our end goal is to develop an open-source, open-access model that may be used by anyone, so model simplicity and compatibility with a variety of preference elicitation approaches could support uptake by groups seeking to intervene in a FERC relicensing process.

The most appropriate participatory approach for hydropower dam decision support is SMCE. SMCE rates 4 – 5 on our 2-dimensional scale (Figure 24); it is a true group participatory approach. Like WS, SMCE is a generalizable participatory approach that fits with multiple types of models: AHP [91], NAIADE [92], [93], CPSS [58], and SDS [92]. Flexibility is key in our research, where hydropower dam decisions are site-specific, sometimes garnering intense public attention and other times going unnoticed. SMCE also has the potential for integration with other participatory processes, such as SBSE (see [92]), and DAI [58], [92]. As described by Antunes et al. [91] and Kallis et al. [92], SMCE helps to identify key stakeholders and DMs early in problem scoping, prompting researchers to circle back to DMs at different stages in modeling to gather input or feedback, potentially engaging a group in deliberation or discussion over shared preferences, and finally require member-checking of results with DMs, a two-way information exchange. Studies using this approach were all rated as deeply engaging. Other, equally participatory approaches are deemed not appropriate (e.g. Delphi, Mediated Modeling, and Gaming and Simulation) because their application appears to require too much DM time commitment (see [30], [35], [55]), over multiple meetings (or even over years, as with Manthrithilake and Liyanagama [63]). These approaches, while likewise engaging, are too intensive for our purposes. The early and sustained engagement of SMCE is useful for hydropower dam decision making because latecomer stakeholder needs can shift or derail processes where there has been no long-term dialogue or trust-building. The iterative nature of the SMCE approach, which is grounded in an understanding of who is important to the problem context, is attractive where trust takes a long time to build and can be lost in an instant. SMCE with WS could fill the gap we see in our 2-dimensional identification scheme, where simple, easy-to-understand models might be paired with group participatory involvement in modeling. Testing simpler models with varying levels of stakeholder involvement may shed new light on MCDA modeling in terms of meeting DM needs.

A serious limitation to this review is the lack of information that studies provide about DM experience. A total of 20% of the studies we review either use hypothetical or equal preference information to achieve a decision outcome. Three studies are purely hypothetical, with no participants or results to report. This focus on model description may be a result of research applications designed without consideration for problem-solving usefulness to DMs. Where real DMs are involved, basic aspects of research design are systematically unreported, particularly where groups of DMs are involved: how long did workshops or group meetings last? How far apart did the meetings take place? Did participants attend in person or virtually? Was the model or decision support tool used directly by participants, by a facilitator, or was it driven by a researcher? How was the final decision outcome achieved (consensus, compromise, majority vote)? In many of the studies reviewed here, we observe that the authors place analytical emphasis on the decision tool or model itself, rather than on the decision process it supports. Depth of engagement was particularly challenging to assess because of limited methodological detail (this was true across the board).

4.6. Conclusion

This first pass at model and process selection was enough to inform early stages of development and planning, but we wish to reiterate the need to evaluate both models and participatory processes with a more nuanced approach, with a thoughtful rubric designed for assessing model, process, and outcome (unreported in many studies reviewed here). In participatory MCDA literature, engagement-based questions are simply not addressed *ex-post*, and we have found little evidence to suggest that researchers are considering them *ex-ante*, except Peniwati [191], Cinelli et al. [188], and Marttunen et al. [171]), who each outline a more nuanced collection model assessment metrics (including participatory impacts), but still limit the discussion of usefulness to the decision maker. Of the studies we review here, only three ([195], [200], [201]) evaluated DM participation (e.g., group dynamics and content of discussion) systematically. The problem is widespread: where performed, critical assessment is communicated in an offhand way (i.e., evaluation appears *ad hoc*). This problem is likewise noted by Marttunen et al. [171]. Recent evaluation methodologies focus on MCDA model selection (see [166]–[168]) and ignore participatory considerations. Our exploration into Depth of Engagement and Model Complexity admittedly scratches the surface on the suite of tradeoffs researchers make in participatory MCDA research design, but we make a key contribution to the academic conversation: (a) an explicit definition of two dimensions for MCDA evaluation and (b) a thorough demonstration of their use through identification of 25 documented applications.

While we hypothesized that Depth of Engagement imposes a practical limit on the Model Complexity dimension, implying a direct tradeoff where neither dimension may be maximized without sacrificing some level of the other, this does not appear to be the case. Instead, other practical factors such as time, which appeared to allow deep engagement in complex modeling (as in SDS [92], [207], [208]), or limit conversation (as in silent negotiation [204]), seem to play into researcher choice of the model or participatory approach. Time is not something we focused on in our 2-dimensional assessment, but it begs further analysis because considerable time and effort are needed to develop a detailed and accurate model and collect and harmonize data for use in that model while also developing and implementing an appropriate DM engagement process. Systematic critical evaluation of participatory MCDA applications is needed to be able to address questions about the ultimate usefulness of the model to decision makers [188], both *ex-ante* and *ex-post*. Our 2-dimensional scheme (e.g., Model Complexity and Depth of Engagement), a precursor to such a task, provides a focused and rapid means of assessment. MCDA is often touted as an approach to structuring natural resource management decision making (see [71]), but until researchers begin to describe in detail the participatory processes and evaluate the DM experience of using MCDA tools and working within its processes, we will not have a true sense of MCDA's effectiveness or practicality for real-world participatory decision support.

5.0. A CASE STUDY OF MULTI-CRITERIA DECISION ANALYSIS (MCDA) AS PARTICIPATORY DECISION SUPPORT

Abstract

Hydropower licenses are usually granted by the Federal Energy Regulatory Commission (FERC) for 30 to 50 years, making relicensing a key opportunity for reassessment of the privately-owned project's impacts on the public waterway. There are barriers to formal participation for non-dam-owners in relicensing, so I led the development of a participatory Multi-Criteria Decision Analysis-based Dam Decision Support Tool (DDST) to help overcome some of those barriers and support decision making. The DDST was designed with input from real dam decision makers in Maine and focused on a set of hydropower dams coming up for relicensing in the Penobscot River in the next 10 years. This case study of the DDST, which includes 3 embedded 'test' studies (stakeholder participatory workshops), demonstrates how the DDST was designed to support users and provide *access to information* and *build capacity* for participation in FERC relicensing. I evaluate the DDST and the participatory experience using model outcomes, survey data, and a two-dimensional assessment. I find that while the DDST provides users with information and supports learning, both key contributions to early-stage relicensing conversations, usability may be a moving target.

Keywords: MCDA, Participatory Decision Support, Weighted Sum, Analytical Hierarchy Process, Hydropower

5.1. Introduction

While much of the United States' hydropower capacity is owned and regulated by federal agencies (e.g., Bureau of Reclamation owns some of the largest hydropower plants, including as Hoover Dam), a majority of the hydroelectric powerplants in the U.S. fleet are privately owned [4]. The Federal Energy Regulatory Commission (FERC) licenses and regulates these (typically small (<10 MW) to medium (10 MW – 50 MW)) privately owned hydropower dams in the U.S. [1], [212]. The FERC hydropower licensing process is long and complex, averaging 5 years but potentially lasting longer than a decade [66]. FERC carefully deliberates over the site requirements after reviewing the owner's license application, as well as comments from regulatory agencies, interest groups, and the general public. Then, FERC grants or denies a license to the owner for continued operation. Licenses are usually granted to the dam owner (hereafter licensee) for 30-50 years [99], underscoring the importance of the relicensing process as a critical opportunity to reassess the dam's environmental, social, and economic impacts before the license is *extended for another 30-50 years*. FERC is mandated by the Supreme Court to consider each license application as a blank slate (i.e., as if the licensee were seeking approval for new dam construction in a free-flowing section of the river) [213], [214]. During the relicensing process[16], FERC requires the licensee to hold public hearings to ensure that actors (stakeholders, or folks with a direct interest in the decision outcome; i.e., the general public and formally recognized groups like non-profits, waterfront homeowner associations, businesses, and community groups, as well as entities with legal status in relicensing processes such as tribes and regulatory agencies) may express concern with or support for hydropower operations [1], [99]. The FERC process creates space for actors to get involved legally and have their concerns entered into the official docket (i.e., the legal license record).

[16] I refer to FERC's Integrated Licensing Process (ILP). There are other possible processes a dam owner can use, but the ILP is recommended by FERC and is most common.

The boundaries to participation in FERC relicensing are challenging to bridge; actors need *access to information* that is important to FERC (e.g., cost data or revenue estimates), as well as *capacity to participate* in a way that is meaningful to FERC which often equates to time and money spent in research, meeting attendance, and cultivating an understanding of FERC processes.

Northeastern U.S. hydropower relicense applications will spike (135 anticipated) in the next 10 years[17], so the issue of meaningful participation is regionally pressing. The issue is also nationally relevant, as the U.S. is expected to see 294 relicense applications in the same period, making Northeastern U.S. applications ~46% of the total volume[18]. My research seeks to support actors in FERC hydropower dam relicensing by spanning process boundaries of *information access* and *participation capacity*, two key issues limiting meaningful participation. *Information access* is a process boundary preventing knowledge exchange by limiting the number of voices in the decision-making process through exclusion [215]. It refers to asymmetries in knowledge between actors that stem from differing expertise or data, making discussion challenging. The proprietary, specific, up-to-date information that licensees have at their disposal is considerable. Other actors have access to delayed filings through FERC's e-library, which typically depend on licensee reporting. FERC also restricts documentation during relicensing to actors legally involved in the process (this information is later released to the public via the FERC e-library). Stakeholders have access to different types (and amounts) of information during the decision-making process, and knowledge is not equally accessible to all entities. For instance, interviews with dam decision makers indicate that non-owner actors lack necessary economic information to make arguments about the value of hydropower projects to the state of Maine, thereby limiting their potential impact in the relicensing process. Boundary objects (e.g., decision support tools) have the potential to set users on equal grounding with *access to information* pertinent to decision making [216]–[218].

[17] Calculated using FERC Expected Relicense Projects FY 2019 – FY 2033 (last updated 09/25/2019), available on https://www.ferc.gov/industries/hydropower/gen-info/licensing.asp.
[18] Calculated using FERC Expected Relicense Projects FY 2019 – FY 2033.

I identify *participation capacity* as a process boundary in dam decision making because it constrains actor influence and standing in the dam decision process, thereby threatening effective participation [215]. I define *participation capacity* as ability (know-how), resources (in terms of labor or capital), or time (and time is money) to actively participate (e.g., filing as a legal intervenor) in relicensing. Lack of participation capacity limits the number of perspectives represented in relicensing. In interviews, several stakeholders expressed concerns to me that capacity asymmetries leave certain groups without a voice in the dam decision. *Participation capacity* is a boundary that may be addressed through boundary-spanning activities (e.g., decision support workshops) which bring people and resources together to co-produce knowledge.

Multi-Criteria Decision Analysis (MCDA) is a structured framework that breaks a decision into components (decision criteria and alternatives) represented in a decision matrix (*n* by *m* table, with *m* columns) populated with decision criteria data. MCDA then incorporates decision maker (DM) preference information with the decision criteria data to generate a ranked set of alternatives so that the DM may make an informed decision. MCDA extends standard cost-benefit analysis because it handles qualitative (as well as quantitative) information and does not require monetization. Simply put, MCDA is a useful way of "laying everything out on the table", because it puts different (potentially disparate) relevant decision criteria in conversation with one another, so that the decision maker may compare their options in an informed way. In Chapter 4, I reviewed the literature on participatory decision support (with a focus on MCDA) for water resource management. Responding to a practical need for rapid model assessment, I developed a two-dimensional (Model Complexity and Depth of Engagement) method for *ex-ante* and *ex-post* assessment and demonstrated its use by evaluating 25 participatory decision support application studies. Model Complexity is the dimension measuring complexity: the model's mathematical computations, its software specificity, and the level of researcher support needed to run the model or interpret results. Depth of Engagement measures the extent to which the DM is involved in both modeling and the decision process. In my assessment of application studies, I identified Weighted Sum (WS) MCDA as a suitable approach for group decision support. This assessment also identified a clear gap where minimally complex models are seemingly not being used for group engagement. If it is designed with boundaries in mind, group participatory WS MCDA has the potential to focus conversations about dam futures and support (in a minimally complex way) stakeholder groups seeking to participate in a FERC relicensing process. My research question is: *how can an MCDA-based Dam Decision Support Tool be designed to provide information access and build capacity for participation in dam decision-making processes?*

This work is part of a National Science Foundation (NSF) Established Program to Stimulate Competitive Research (EPSCoR) RSII Track-2 funded multi-year, multi-state, multi-disciplinary research project across Maine, New Hampshire, and Rhode Island, aimed at improving the science behind dam decisions. The NSF-EPSCoR project, called "The Future of Dams", included researchers from fields as diverse as civil engineering and environmental communication. The research team specific to the development of the Dam Decision Support Tool (DDST) included: an interdisciplinary social scientist, an interdisciplinary energy researcher, a geologist, a software engineer, an environmental communications researcher, and a digital ethnographer, all part of the Future of Dams (FOD) project.

5.2. Methods

I employ embedded case study design in my research (see Yin [219]), where the case is DDST development, encompassing 3 embedded 'test' studies [219], as the DDST evolved in three distinct versions that were each tested in a workshop context (Figure 25). The DDST research team held (Study 1) a June 2018 workshop with 18 FOD researchers using DDST 1; (Study 2) a March 2019 workshop with 35 students using DDST 2; and (Study 3) an October 2019 workshop with 9 stakeholders/DMs using DDST 3. The total sample size for my case is 52 participants, which is sufficient for case study research [220]. I define these workshops as studies on both tool development (i.e., how did the tool evolve) and user interaction with the tool because the model development was an evolutionary process within the larger case. The causal claim I make is that the DDST and participatory decision-making process in the workshop(s) reduce boundaries of *information access* and *participation capacity* by providing a structured, interactive space for the user to get to know site-specific data and explore the potential impacts of their preferences on the recommended outcome. In case study research, causal claims are supported through "process tracing" [221] or through linking together the "chain of evidence" [219], [222]. Both process tracing and linking the chain of evidence help me establish dependability and credibility in research claims [223], [220], motivating a narrative and substantiating claims about cause and effect [221]. The case study evidence I use includes researcher observations during the workshop activities and post-survey evaluation of workshop activities and materials [219]**.** I develop an institutional understanding using interviews and FERC license documents.

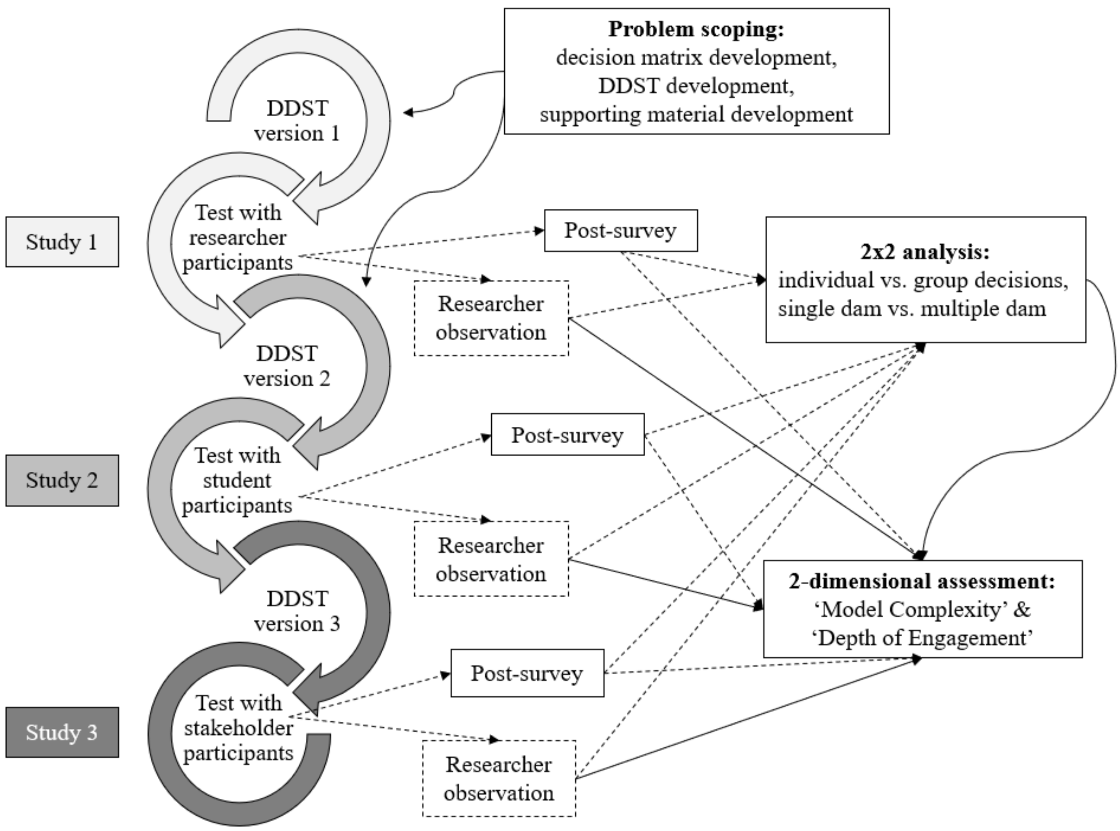


Figure 25. Case study design: iterative development of the DDST across embedded 'test' studies. Solid lines indicate direct inputs/outputs and analyses (boxes), while dotted lines indicate more interpretive inputs/outputs.

The problem scoping process (section 5.2.1) determined the selection of decision criteria and alternatives for the MCDA decision matrix, shaped our approach for DDST 1, and (after Study 1) informed the development of supporting materials like Dam Factsheets and Dam Data Tables (i.e., the MCDA decision matrix for a dam, populated with site-specific data). Lessons learned from Study 1 (gleaned primarily from post-survey and researcher observations, section 5.2.2) informed the DDST 2 and workshop design for Study 2 (section 5.2.3), while lessons from Study 2 informed DDST 3 and workshop design for Study 3 (section 5.2.4). Post-survey and researcher observation are considered outputs for interpretation in the cross-comparative analysis (section 5.2.5), which include both 2x2 analysis and 2-dimensional assessment of ‘Model Complexity’ and ‘Depth of Engagement’, rating spectra developed in Chapter 4 as a way to consistently compare and assess MCDA application studies, many of which seem to be missing ex-post evaluation altogether. While problem scoping heavily informed DDST 1 and DDST 2, post-survey and researcher observation were the primary driver in the development of DDST 3. The DDST evolved across the three studies, as did the set of support materials and workshop design (Appendix K).

While most organizational elements (pre/post survey, individual and group MCDA activities, were consistent across all 3 workshops, there were a few key variations. For instance, the time allotted was different, as was the decision scope, participant recruitment strategy, and the total number of participants. In Studies 1 and 2, participant recruitment was opportunistic because the research team was interested in pilot-testing the DDST and workshop design before use with stakeholders. In Study 1, we invited FOD researchers to attend a half-day workshop prior to a multi-day research meeting. In Study 2, we invited a class of University of Maine students to engage in hands-on learning about MCDA and dam decision making. In Study 3, participant recruitment was targeted. We invited interview participants representing a cross-section of stakeholders and decision makers with experience with or some exposure to hydropower relicensing. We also reached out to groups mentioned in interviews (snowball sampling) to increase the diversity of perspectives represented. We were intentional about our invitations and numbers, attempting simultaneously to keep the group small (with negotiation discussions in mind) and balanced in terms of perspectives broadly representing hydropower interests, fish interests, tribal interests, and town/city interests. We were unable to garner participation from hydropower owners or towns/cities bordering the river. In all studies, consent forms (Appendix O) explained that participation in research was voluntary, at-will, and participants could decline to participate or leave at any time.

We tested different software programs (Microsoft Excel and R Shiny ([224])) and different approaches to MCDA: Analytical Hierarchy Process (Study 1 used AHP and WS, described in detail in section 5.2.2.1.), and Weighted Sum (Studies 2 and 3 used WS, described in detail in section 5.2.3.1.). Similarly, some of the DDST versions included not only MCDA but also a Multi-Objective Genetic Algorithm (MOGA), a model optimizing tradeoffs between decision criteria to identify scenarios (sets of decision alternatives for multiple dams) in the decision scope. This means that each of the studies was a snapshot of a stage in DDST development. Support materials indicate background information about the project and DDST version (Appendix K, section 1.2., 2.2., and 3.2.), Dam Factsheets (Appendix K, section 2.3. and 3.3.), or Dam Data Tables (Appendix K, section 2.4. and 3.5.). Participants were given support materials ahead of time and asked to review them before attending the workshop (this was considered background reading). All studies included a pre-survey. Round-robin introductions refers to an activity where participants, researchers, facilitators all went around in a circle and introduced themselves and mentioned their reason for attending because participants did not necessarily all know each other (the FOD researchers knew one another, but there were new members of the team present at the June 2018 workshop).

The icebreaker activity, specific to study 3, refers to an activity aimed at helping participants get to know one another, building rapport, and improving facilitation; this late addition to the workshop design was because there was not enough time for it in the other two studies, and the participants in the first two workshops knew each other before attending (e.g., researchers in the same grant, students in the same class), so there was no need. Study 3 also uniquely had a few minutes dedicated to collectively agreeing upon group commitments. This additional brief activity was aimed at building rapport and respect amongst participants, which was especially important in Study 3, where the professional roles of the participants (i.e., their representation of official groups or organizations) could potentially lead to conflict, as in real dam decision making. Group commitments were something that the facilitator (one of our DDST research team) referred to when certain voices started to drown out others. The presentation on MCDA oriented participants to the decision scenario, activities for the day, and general mechanics of MCDA. Individual MCDA was a solo activity between the individual participants and their laptop computer (provided by the DDST team in Study 3; brought in by participants in Studies 1-2), where they consulted support materials, followed the directions guiding them through the model, entered their preferences, and reviewed results. In the two longer workshops (June 2018 and October 2019) we offered a meal between individual and group rounds of MCDA (Table 26), and in both cases participants elected to make it a working meal, where they shared a meal and worked in groups to finish either the individual or group MCDA activity. The group MCDA activity was negotiation-based, where individuals were tasked with coming to a shared set of preferences for each criterion or decision alternative (depending on the type of MCDA used). The debrief discussions were held after individual MCDA and group MCDA activities to allow participants a chance to process the experience together. Finally, the post-survey was something participants completed outside of the workshop (except for study 3, where most participants completed the survey onsite), and the social hour was an add-on to the two longer workshops for participants to relax afterward. No one attended the social hour in Study 3 because it was after the end of the workday and many participants had to travel a while to return from the workshop.

Table 26. Case study design overview, with comparison across embedded studies.

Attribute	**Study 1**	**Study 2**	**Study 3**
Workshop date	Jun. 2018	Mar. 2019	Oct. 2019
Time allotted (hours)	4	3	8
Recruitment strategy	Opportunistic	Opportunistic	Selective
No. participants	18	35	9
Participant type	Researchers	Students	Stakeholders/DMs
DDST software	Excel	R Shiny/ Excel	R Shiny
MCDA type	AHP	WS	WS
MOGA	Y	Y	N
No. decision alternatives	6	5	5
No. Criteria	7	11	14
Decision scope (no. dams)	>20	3	8
Support materials	M, R,	M, R, F, D	M[†], F, D

Table 26. (Continued)

Attribute	Study 1	Study 2	Study 3
Background reading requirement	Y	Y	N
Pre-survey	Y	Y	Y
Round-robin introductions	Y	N	Y
Icebreaker activity	N	N	Y
Group process commitments	N	N	Y
Presentation on MCDA	Y	Y	Y
DDST tutorial	Y	N	Y
Individual MCDA	Y	Y*	Y
Debrief of individual MCDA	Y	N	Y
Meal/Break	Y	N	Y
Group MCDA	Y	Y	Y
Group size (no. people)	3-5	4-6	9
Researcher facilitator(s) for group work	N‡	N‡	Y
Debrief of group MCDA	Y	Y	Y
Post-survey	Y*	Y*	Y
Social hour (after the workshop)	Y	N	Y°

Abbreviations: Y = yes, included; N = no, not included; M = map(s); R = rose plot; F = Dam Factsheets; D = Dam Data Tables; NPD = non-powered dam; * completed on their own, outside of the workshop; ‡ researchers observed, rather than facilitated; †a map was included before the preference elicitation, but not as a result; °participants were invited to, but did not attend, a social hour after the workshop.

5.2.1. Problem Scoping

The first step in this research was to develop an MCDA decision matrix (section 5.2.1.1), which is a table of data for different decision criteria (i.e., factors, attributes important to the DM) across a set of decision alternatives (project options to choose between). To build an MCDA decision matrix, I used a mix of interviews, academic literature review, FERC license document review (see Ch. 3 for a description of this process), and hydropower dam site visits to ground this work in the realities of hydro operations. The interview protocol, developed collaboratively amongst Future of Dams researchers engaged in a 'Stakeholder Working Group' [225], was semi-structured with additional probing questions or prompts about research topics as needed [226]. The collaborative approach to interview protocol development, which was facilitated through Zoom video conference software [227], allowed our multi-state, multi-institutional research team to coordinate our efforts for intentional and efficient data generation with interviewees. Protocol questions addressed multiple topics across the research project for cross-disciplinary analysis. Interviewees were selected based on the mention of their name(s) in a Media Discourse Database (news media article dataset compiled by searching local and national sources using the term ‘dam removal’ [228]), affiliation with the PRRP, and snowball methods (i.e., identified by other stakeholders). Social science researchers on the Future of Dams project team (including me) interviewed key Maine and federal stakeholders (N=26), people who had been part of dam decision processes in the past (non-profits, federal regulatory agency representatives) to learn about the kinds of decision criteria and alternatives that they consider in their own dam decisions. Members from the DDST research team attended 5 informal meetings (including site visits to dams in the Penobscot River watershed (including West Enfield) and other basins in Maine and Connecticut) with licensees or licensee representatives.

Originally, our DDST research team planned to use a Media Discourse Analysis to shape our decision matrix but realized very quickly in problem scoping that the search term ‘dam removal’ likely left out hydropower-specific issues for operating dams. Similarly, we realized that the database was reflective of how a few key newspapers describe issues at a dam, which may be more indicative of the journalist’s (sometimes limited) understanding of the issues at a dam site than fully representative of the DMs or participants in a relicensing process. We ultimately used the Media Discourse Analysis Database as a check for our interviews, comparing a decision matrix developed from interviews and literature review with a second decision matrix (Raffier [229]), developed from the Media Discourse Analysis Database.

I reviewed the academic literature on small-scale hydropower (Ch. 2), identified applications others have studied, and communicated my findings to the DDST research team. Likewise, I reviewed the MCDA application literature (Ch. 4) to get a sense of the different decision criteria others have used in participatory hydropower dam operation and water resource allocation decisions. FERC license document review helped the DDST research team to better understand the institutional roles of different actors in relicensing and start to think about site-specific data. First, I navigated to the FERC Online eLibrary and selected “General Search”, setting the date range to “All” and the category to “Issuance” only (not submittals). Then, I selected the Hydro Library and entered the docket number for the sites I was interested in (data that I had collected previously from the New England Dams Database [230]). Dockets are the collections of all the files relating to each specific hydropower project license. So, for instance, the Penobscot Mills Project will have a dedicated single docket (for 5 dams), and so will the West Enfield Dam. I read the license issuance documents within each relevant docket to get a sense of hydropower capacity and turbine specifications (how many, what kind), operations (i.e., run-of-river or store-and-release), and dam construction materials. The license documents were also used in the development of Dam Factsheets (Appendix K, section 2.3.2.), which include information on site ownership history, technical specifications, stakeholders, past names of the dam, and fish passage facility information. Some of the license data values were used for decision criteria data estimation: annual electricity generation, annual CO2 emissions reductions, and annuitized project costs were harmonized or estimated using hydropower project capacity data from FERC licenses in Chapter 3. This background research drove our DDST research team's decisions about which decision criteria and alternatives to include.

Throughout the development process, members of the DDST research team also performed member-checks with key stakeholders at different stages in DDST development, as well as frequent (~quarterly) peer check-ins with other (1-3) researchers on the Future of Dams project (specifically, the Dam Factsheets were reviewed by multiple researchers, multiple times) and the rest of the DDST team to verify the credibility of interpretations from researchers observations (Figure 26). The team's member-checks with stakeholders took place throughout 2019, beginning in April, where we shared our Dam Factsheets, decision matrix/site-specific data matrices, and DDST 2 user interface with tribal nation stakeholders in a focus group setting. The feedback about the decision matrix led to email-based member checks about the Dam Factsheets with tribal nation stakeholders absent from the focus group. Later in the year, we performed focus group-style member checks with other stakeholders who were involved in another project, focused on collaboratively developing an evaluative rubric with which to assess workshop 3 (paper forthcoming). Again, we received some email follow-up (which I include here as a form of member check) about the proposed decision criteria and alternatives. Ultimately, the feedback during development let to a set of supporting materials that were integrated into the DDST 3 itself as a series of web links.

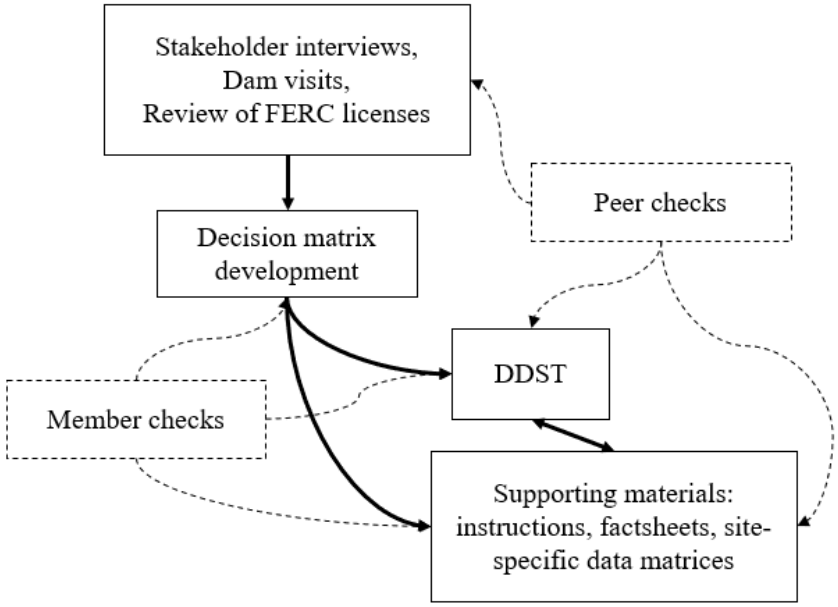


Figure 26. Detail of problem scoping process and output flow (decision matrix, dam decision support tool, supporting materials). Note: this depiction of the process is not linear; e.g., the decision matrix was revised on more than one occasion, as were the supporting materials.

5.2.1.1. Decision Matrix Development

I used stakeholder interviews and a review of the MCDA literature (see Ch. 4) to generate a set of decision criteria and decision alternatives for use in a decision matrix for MCDA. In MCDA, decision alternatives are defined as the possible project options for a dam. Decision criteria are usually defined as factors or attributes (e.g., costs, carbon emissions, community identity, properties impacted) upon which to compare decision alternatives. Decision criteria are the components to be measured, descriptors of each decision alternative that are defined by units of measurement. In other cases, decision criteria may be unitless. The *n* decision alternatives and *m* decision criteria together make up the decision matrix, an *n* x *m* array populated with criteria performance values (data) for each decision alternative. The role of a decision matrix in an MCDA is to group data for comparison; it describes the decision landscape. I coded interviews deductively for decision criteria and decision alternatives using a codebook collaboratively developed by researchers on the FOD team (Appendix J). My coding was checked by another researcher for intercoder reliability. An interview coding frequency report (NVivo-generated) informed the decision matrix, where decision alternatives were identified using stakeholder interviews (Table 27). "Improve Fish Passage and

Hydropower Generation" was developed by the research team as a combined alternative to reflect other types of license rulings made by FERC. Note that the "Keep and Maintain Dam" decision alternative reflects coding only for "keep dam", and not "maintenance" or "refurbishment", which were coded separately. The latter two codes did not always fall under the general classification of the "Keep and Maintain" decision alternative. It is possible "keep dam" was mentioned more times than is reflected by n=101, but I felt it was more conservative to stick to a clear mention of the decision alternative (e.g., "keep and maintain"). Note: though "Improve Hydropower Generation" was coded comparatively less than "Remove Dam" and "Keep and Maintain Dam" decision alternatives, it is very relevant to dam owners seeking to maximize the profitability of their assets (see Ch. 3).

Table 27. Final decision alternative and criteria list with stakeholder interviews

	Definition	**No. Interviews Coded**	**Total Mentions Coded**	**Per Interview Mean**
Decision Alternative				
Remove Dam	The dam is removed from the body of the river, allowing water to flow freely.	22	478	22
Improve Fish Passage	Fish passage structure(s) installed: state-of-the-art fish lift/elevator, or addition of an eel ladder, depending on the migrating species in the river (may be required by law).	22	221	10
Improve Hydropower Generation	Hydropower generation capacity is increased through the installation or upgrade of turbines.	15	50	2
Improve Fish Passage and Hydropower Generation*	Install some type of fish passage structure and increase hydropower generation capacity through installation or upgrade of turbines. This specific decision alternative was not coded explicitly in interview analysis, because it represents a blended decision alternative.	NA	NA	NA
Keep and Maintain Dam	This is the business-as-usual or status quo option, where the dam remains in place and minimal costs are incurred to ensure dam structural integrity and safety compliance.	19	101	5
Decision Criterion				
Fish Survival (thousands of lbs or tonnes)	Sea-run fish (Atlantic salmon, Alewife, Blueback herring, American eel) biomass estimated using functional habitat above dam *i* for species *k* [18].	22	619	28
River Recreation Area (square miles or kilometers)	Area of connected river section that may increase or decrease with a dam decision alternative, refers to the functional area for whitewater recreation defined by Roy et al. [18].	20	133	6

Table 27. (Continued)

Decision Criterion	Definition	No. Interviews Coded	Total Mentions Coded	Per Interview Mean
Reservoir Storage (cubic miles or kilometers)	Storage potential of the reservoir, based on volume [18].	21	121	6
Annuitized Project Costs (2019 $USD)	Annuitized capital and operation & maintenance (O&M), calculated using a 6.2% discount rate over a 20 year project lifetime and adjusted to $2019, using hydropower project capital expenditure estimates from Hall et al. [36] (including contingency, estimated using values from the U.S. Bureau of Reclamation [10]) and O&M estimates from O'Connor et al. [11], details in Ch.3.	21	151	7
Number of Properties Impacted	Based on potential changes in viewshed or property value, limited to riparian zone within 200 meters of the dam and/or reservoir [18].	14	34	2
Breach Damage Potential (unitless)	Indicates the potential for downstream property damage, injury, and death in the case of a dam breach, based on state dam hazard levels reported by the Maine Office of GIS [231].	17	81	4
Average Electricity Generation (MWh/yr)*	Based on the value listed in the FERC license for each hydropower project, details in Ch. 3.	22	379	17
Carbon Dioxide (CO2) Emissions Reduction (tonnes/year)*	Avoided lifecycle greenhouse gas emissions, estimated using point-source CO2 emissions by fuel type for generators in Maine for 2017 [61], [148], [153], [232], as well as emissions factors for reservoir-based and diversion hydropower see Ch. 3 for details.	13	24	1
Indigenous Cultural Heritage (unitless)*	Importance of the decision alternative for preserving/restoring the culture of indigenous people.	17	61	3
Town/City Identity (unitless)*	Importance of the decision alternative for preserving the existing identity of the community of town/city residents living along the river.	20	148	7
Industrial Historical Value (unitless)*	Importance of the decision alternative for preserving/restoring the industrial historical value of the site.	18	55	3
Aesthetic Value (unitless)*	Importance of the decision alternative for improving or preserving the appearance, scenic value, smell, sound.	20	93	4
Public Health (unitless)†	Importance of the decision alternative for improving public health connected to air, water, and land pollution.	-	-	-
Socio-Environmental Justice (unitless)†	Importance of the decision alternative for mitigating negative environmental effects targeting disadvantaged groups.	-	-	-

*Added in DDST 2, after comments from researcher participants that we needed additional site-specificity† Added in DDST 3, after member-checks with stakeholders (i.e., ground-truthing or credibility checking of the model in development—did the decision criteria make sense, or reflect their interests?)

5.2.2. Study 1 Design

Many biophysical scientists recommend multi-dam approaches to decision making [17]–[19], primarily due to the downstream impacts of dams in rivers. Locally, the Penobscot River Restoration Project (PRRP), a strategic multi-dam project, caught local, state, and national attention because of the decades-long commitment that went into negotiations and the final agreement to balance fish passage and hydropower generation across multiple dams in the river [19]. The PRRP showed that multi-dam decision making was possible for the Penobscot River, especially where actors could coordinate across interests and management objectives (sea-run fish habitat area being the key decision criterion for non-licensee actors, in this case). For this reason, we selected the entire Penobscot River watershed (i.e., the main stem of the river and all its tributaries) as the scope for participant decisions in Study 1.

In Study 1, we employed a MOGA model (see Roy et al. [18]) in addition to our MCDA. Because we were using the Analytical Hierarchy Process (AHP) model as a means for criteria preference elicitation, the MOGA, a model designed for multi-scale decision making that optimizes multiple criteria at multiple dams (recommending a set of decision alternatives specific to individual dams in the watershed), integrated the actual aggregating and ranking calculations of MCDA (described in section 5.2.2.1). At this phase in model development, AHP preference elicitation results were used as the preference weights for the MOGA-MCDA (section 5.2.2.1). The MOGA output was connected to a Python script for ArcGIS that produced a map of the results, with a color-coded indication of the decision alternative for each dam and a rose plot of criteria-specific preference weights for reference.

5.2.2.1. DDST 1: watershed-scale AHP-MOGA with Excel UI

DDST 1 was based on the AHP approach to MCDA. AHP is a type of MCDA that breaks down the decision problem into a hierarchy. AHP preference elicitation, its most defining feature, focuses DM preference judgments onto a single criterion at a time [183] and takes the form of a series of pairwise comparisons between alternatives. It is the most common type of MCDA in natural resource management decision research [233]. Advantages to the AHP are allowance for inconsistency in DM preference judgments (detailed discussion in Ch. 4), and thorough preference elicitation (i.e., for each decision criterion-alternative pair, detailed discussion in Ch. 4). These factors motivated my selection of the AHP for DDST 1. While AHP is compared to other MCDA approaches in Chapter 4, it is important here to discuss the methodology stepwise to build a clear foundation for understanding the DDST 1. In AHP, DM preference values (a) are elicited from the pairwise comparisons of m decision alternatives on n criteria. DMs "locally" compare decision alternatives to each other under each decision criterion, where DM preference values are then assembled into a consistent matrix [A] (Eq.70) for each criterion (i.e. one matrix specific to each criterion), where each value of the main diagonal is equal to unity, and every entry outside of the main diagonal has a reciprocal entry (e.g. $[a_1/a_2], [a_2/a_1]$). The reciprocal entries imply that the comparison of a_1 to a_2 is the inverse of the comparison of a_2 to a_1, which is critical to maintaining consistency [183] (Equation 54). This process is repeated for each set of decision alternatives under every decision criterion (resulting in [A_1] …[A_n]), and then again for the criteria themselves, where DMs "globally" compare decision criteria directly to other decision criteria, and the "global" preferences are assembled into another consistent matrix [A_G]. The total number of consistent matrices as this point would be $N+1$ (where N = total criteria) Most representations of AHP skip this next computational step, it highlights key differences from the WS method, which I used for DDST 2 (section 5.2.3.1.) and 3 (section 5.2.4.1.). The raw DM preference rating values are standardized by dividing the raw rating (e.g. a_{12}) by the column sum. This is called the standardized matrix [S_1] [183] (Equation 56). This process is repeated for all consistent matrices until the full set of standardized matrices is [S_1] …[S_n]. In the aggregation step, we took the standardized values from each standardized matrix ([S_1] …[S_n]) and averaged them by row using the arithmetic mean method (Equation 57). We then repeated for each row of each standardized matrix (recall, there will be $N+1$ standardized matrices), resulting in a scalar local preference weight for each alternative under each criterion. Equation 57 results in a score, x_{11}, that can be compared to the aggregated score in WS MCDA (more on this in section 5.2.3.1.), but it is important to note that in our example, the AHP scores are calculated using only DM preference values; no actual decision criteria data are included in the calculation, recalling that the MCDA data and preference aggregation happens in the MOGA portion of DDST 1. The local preference weights matrix [*X*] is the aggregation of the preference weights for each alternative under each criterion (Equation 58).

$$[A_1] = \begin{bmatrix} a_1/a_1 & a_1/a_2 & \cdots & a_1/a_m \\ a_2/a_1 & a_2/a_2 & \dots & a_2/a_m \\ \vdots & \vdots & \ddots & \vdots \\ a_m/a_1 & a_m/a_2 & \cdots & a_m/a_m \end{bmatrix} \tag{54}$$

Or, more familiarly:

$$[A_1] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1m} \\ a_{21} & 1 & \dots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & 1 \end{bmatrix} \tag{55}$$

where a = the DM rating for pairwise comparison, which may take on values 0< a< 1 or a>1.

$$[S_1] = \begin{bmatrix} 1/\sum a_{m1} & a_{12}/\sum a_{m2} & \cdots & a_{1m}/\sum a_{mn} \\ a_{21}/\sum a_{m1} & 1/\sum a_{m2} & \dots & a_{2m}/\sum a_{mn} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1}/\sum a_{m1} & a_{m2}/\sum a_{m2} & \cdots & 1/\sum a_{mn} \end{bmatrix} \tag{56}$$

$$\frac{\left[\left(\frac{1}{\sum a_{m1}}\right)+\left(\frac{a_{12}}{\sum a_{m2}}\right)\dots+\left(\frac{a_{1m}}{\sum a_{mn}}\right)\right]}{m} \;\Rightarrow\; x_{11} \tag{57}$$

$$\begin{bmatrix} x_{11} \\ x_{21} \\ \vdots \\ x_{m1} \end{bmatrix} \text{ and } \begin{bmatrix} x_{12} \\ x_{22} \\ \vdots \\ x_{m2} \end{bmatrix} \;\dots\text{and } \begin{bmatrix} x_{1m} \\ x_{2m} \\ \vdots \\ x_{mn} \end{bmatrix} \Rightarrow \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \dots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} = [X] \tag{58}$$

The local preference weights matrix [*X*] is a compilation of the weights for all of the criteria-alternative specific preferences. The calculations (Eq. 56 – 58) are also applied for the criteria standardized matrix (again, we have *N+1* total matrices). Averaging standardized criterion values (*c*) by row using the geometric mean method results in a vector of global preference weights (one weight for each criterion, equivalent to the “preference weight” in WS MCDA). Together, these global weights make up the global weights vector, ***W***. Finally, the AHP uses WS methods to aggregate (Eq. 61) and rank the decision alternatives based on DM preferences (Eq. 62). These final two steps occur in the MOGA portion of DDST

1. The MOGA takes the local preference weights matrix and the global weights vector as inputs. The MOGA then applies these values to the Pareto-optimized set of decision criteria (i.e., the frontier of possibilities where no one criterion can be increased without decreasing another, see [159] for a discussion of how Pareto optimization is considered in natural resource management) to identify the set of recommended decision alternatives for the watershed.

$$\frac{\left[\left(\frac{1}{\sum c_{n1}}\right)+\left(\frac{c_{12}}{\sum c_{n2}}\right)\ldots+\left(\frac{c_{1n}}{\sum c_N}\right)\right]}{N} \rightarrow w_1 \tag{59}$$

$$\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \boldsymbol{W} \tag{60}$$

$$[Y] = \boldsymbol{W} * \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \ldots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1m} \\ y_{21} & y_{22} & \ldots & y_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix} \tag{61}$$

where $x_{11} – x_m$ = the standardized decision alternative scores; and [Y] = weighted criteria matrix.

$$\boldsymbol{Z} = \sum_{m=1}^{n} y_{mn} = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_m \end{bmatrix} \tag{62}$$

*where **Z** is the vector of summed weighted criterion scores specific to each decision alternative ($z_1 – z_m$).*

This final ranking is considered cardinal in AHP. In this way, AHP is a useful way to structure the decision based on DM understanding of the problem, to narrow the discussion to a smaller set of decision alternatives. I have mentioned several times now that the MOGA portion of the DDST 1 was where the MCDA calculation took place (hereafter MOGA-MCDA). This methodological choice was aimed at simplifying the user interface; Roy et al. [18] developed the MOGA-MCDA including a weighted sum calculation as a means by which to narrow down the choice set of Pareto-optimal dam decisions based on simulated preference values. Consequently, the Microsoft Excel user interface of DDST 1 was developed solely as a preference-elicitation activity using AHP mechanisms to obtain local and global preference values for use in the MOGA-MCDA.

In DDST 1, the UI was designed only for preference elicitation and standardization. The Excel user interface using AHP preference elicitation was linked with a MOGA-MCDA, the output from which was a coordinated (mapped) recommendation for dams in the Penobscot River. Roy et al. [18] developed the MOGA-MCDA model using Pareto optimization. The local preference matrix and global preference vector output from the UI, [*X*] and $\boldsymbol{W}$, were inputs for the MOGA-MCDA to help rank the optimized 'scenarios', or collections of dam decision alternatives specific to each dam across the watershed. The MOGA-MCDA optimized the possible scenarios based on the normalized criteria data for the dams in the watershed (Eq. 79 – 80), and once the Pareto optimal scenarios had been generated, the scalar preference vectors $\boldsymbol{Z}$ and $\boldsymbol{W}$ were multiplied together and used to weight the scenarios based on preferences. The MOGA-MCDA output was the mapped top-rank scenario of dam-specific decision alternatives. While his published MOGA model was tailored for the Penobscot, Merrimack, and Connecticut River watersheds with coordinated, watershed-scale dam decisions in mind, Roy modified the MOGA-MCDA in DDST 1 to focus only on the Penobscot Watershed. In DDST 1, the user interface also performed AHP calculations (Eq. 64 – 72), but the aggregation and ranking steps involved only user preferences, not dams data, so AHP pure-preference ranked results were generated as a part of the Microsoft Excel UI (and these data were inputs to the MCDA-MOGA part of DDST 1). Within the MOGA-MCDA, the site-specific dam data were normalized (Eq. 63 – 64) and the preference values were used in the aggregation and ranking calculations (Eq. 61 – 62). Roy input the preference values and created scenario maps 'on the fly' during workshop 1.

$$c_{ij} = \frac{a_{ij} - a_{min}}{a_{max} - a_{min}} \quad where\ a_{min} is\ preferred \tag{63}$$

$$c_{ij} = \frac{a_{\max} - a_{ij}}{a_{max} - a_{min}} \quad where\ a_{max}\ is\ preferred \tag{64}$$

where a_{ij} *= criterion i data value for decision alternative j;* c_{ij} *= normalized criterion i data value for decision alternative j.*

I developed the DDST 1 user interface in Microsoft Excel because my review of the literature (Ch. 4) identified no open-source software programs to support AHP MCDA (SuperDecisions is open access, but I wanted open sourcing to develop a custom user interface, or UI). Excel is a ubiquitous data analysis program, so while not completely open-source, it had the advantage of familiarity and flexibility, since a UI could be developed using Visual Basic for Applications (VBA). The Excel user interface provided brief background information about AHP MCDA (Figure 27) and instructed the user about how to make pairwise comparisons. The user interface was simple, with drop-down menus for numerical preference value selection and supporting information to help the DM make choices (Figure 28). There were 126 pairwise comparisons in this model where the user was prompted to consider each decision alternative pair in the context only of the identified decision criterion. This process was aimed at isolating the decision in a way that prompted the user to think deliberately about the decision alternatives identified [183], [184]. The reason for the extensive number of pairwise comparisons is because AHP elicits both global (criteria-specific) and local (decision alternative-criteria-specific) preferences, whereas other forms of MCDA consider only the former, making AHP a method with one of the more thorough preference elicitation strategies for MCDA (see Ch. 4 for additional discussion on this topic). Buttons with underlying Macros shepherded the user from step to step and then performed the calculations automatically after the user entered 'raw' preference ratings (Eq. 54). In the global preference (criteria vs. criteria) steps, users saw a Production Possibility Frontier (PPF) graph to support them in their thinking about tradeoffs between the two decision criteria (e.g., Figure 29 depicts river recreation vs. number of properties impacted). Our research team thoroughly tested the AHP UI portion of DDST 1 using simulated preference values (e.g., 'hydropower' preferences or 'fish' preferences, where hydropower decision alternatives or fish decision alternatives were favored over other alternatives in pairwise comparisons), but apparently missed an error in the UI's AHP calculation that caused the graphed, ranked outcome (and consequently the MOGA-MCDA result) to show the opposite recommendation than was expected (based on the pairwise comparison judgments). This error impacted the user experience and understanding of the MOGA-MCDA modeling, as well as the UI graph and mapped MOGA-MCDA results (section 5.3.1).

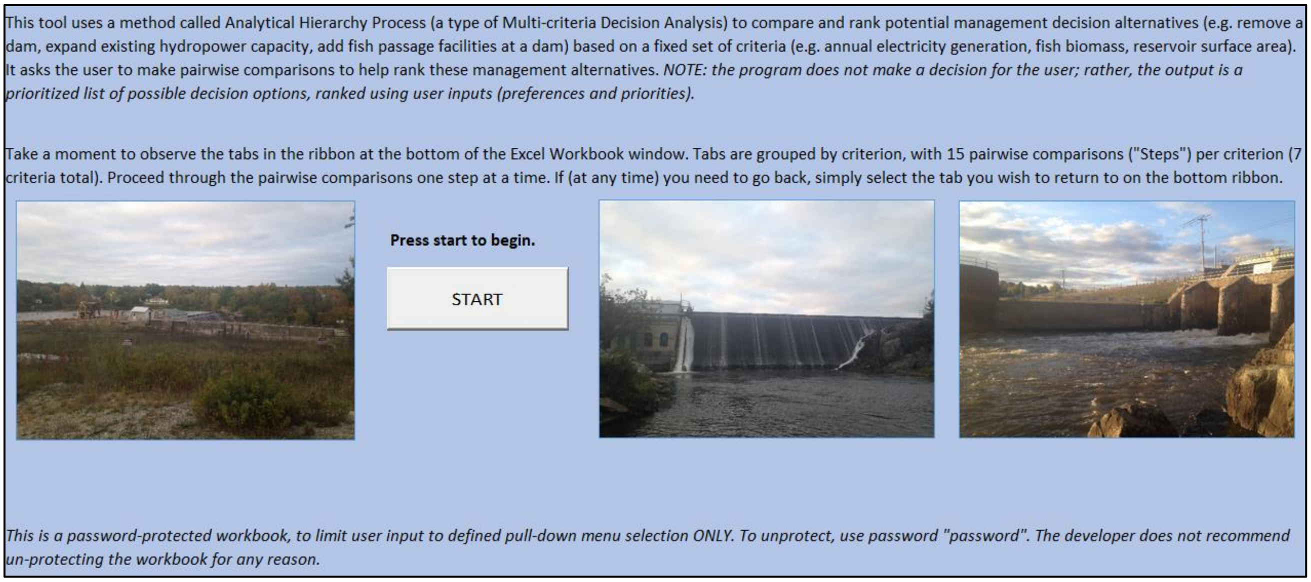


Figure 27. DDST 1 UI: start page and button macro.

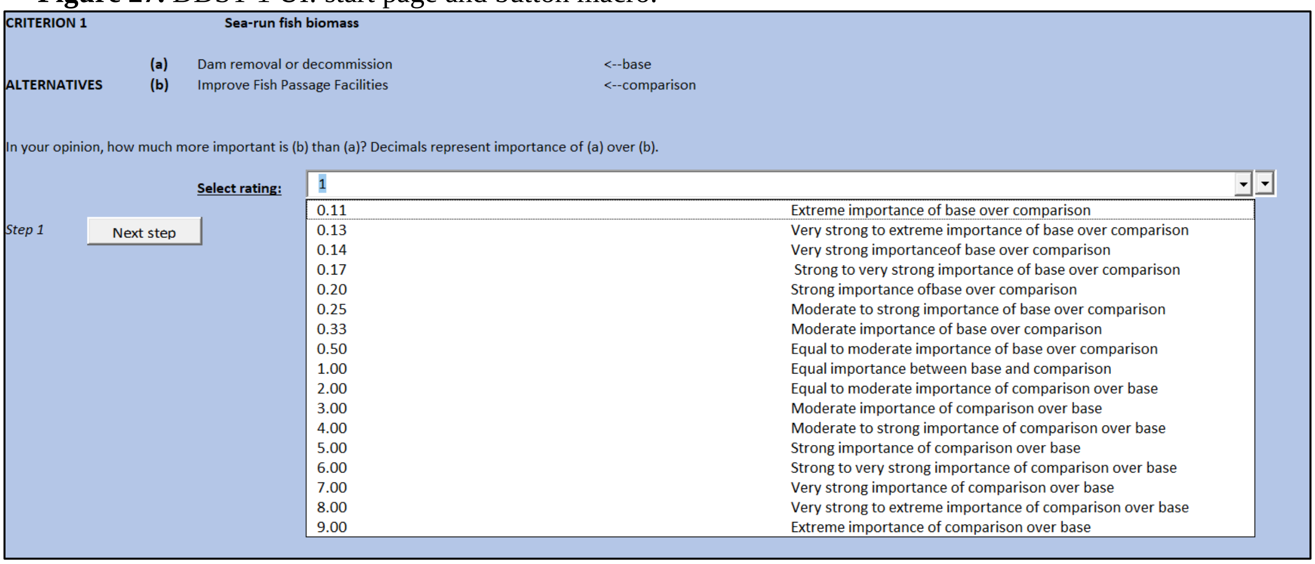


Figure 28. Pull-down menus to limit possible inputs to the Fundamental AHP scale and its reciprocal values.

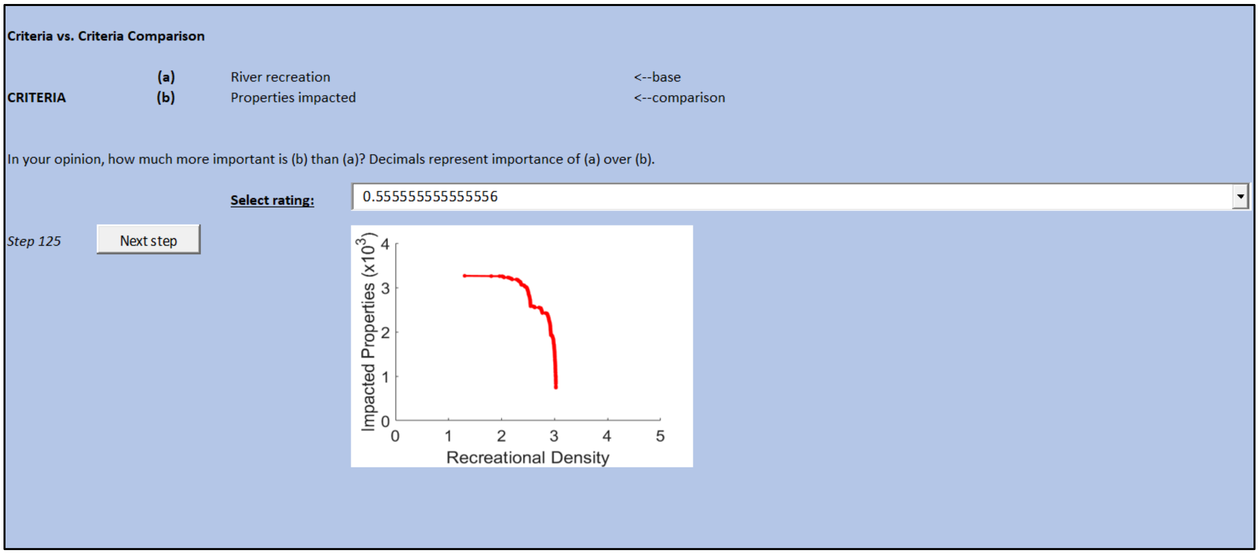


Figure 29. Criteria vs. criteria comparison step with MOGA-generated PPF curve.

Note: decision alternatives and criteria were defined differently in DDST 1. For instance, we referred to the river recreation area criterion simply as “river recreation”, without specifying the units of measurement (km^2). Participants in Study 1 did not receive materials defining the individual decision criteria or alternatives, either; so, a participant seeing “river recreation”, “reservoir storage”, “properties impacted”, “fish biomass”, “hydropower capacity”, “one-time cost”, or “safety” would have needed to ask to clarify how those original 7 criteria were defined. This was an oversight in the user interface development that was immediately flagged for improvement in DDST 2 to reduce the need for researcher support. Decision alternative definitions were also highlighted for improvement. For example, in DDST 1, the user interface described the following 6 alternatives: 1) “improve fish passage facilities” (later simplified to “Improve Fish Passage”), 2) “install turbines or expand existing capacity”, 3) “upgrade or replace turbines” (later integrated with “install turbines or expand existing capacity” and renamed “Improve Hydropower Generation”), 4) “refurbishment, restoration, or maintenance”, 5) “keep dam (do nothing)” (later integrated with “refurbishment, restoration, and maintenance” and renamed “Keep and Maintain Dam”), and 6) “dam removal or decommission” (later renamed “Remove Dam”).

5.2.2.2. Workshop 1: June 2018 FOD Researchers

Participant selection for the first workshop was opportunistic. We invited researchers from academic institutions in Maine, New Hampshire, and Rhode Island, who were all working together on the same Future of Dams 4-year grant, gathered at the University of Maine for a workshop that was an optional activity preceding a bi-annual all-team grant meeting. Note: while our researcher participants had considerable theoretical knowledge about dams and river systems, few (if any) of our participants had practical "boots on the ground" understanding of the FERC process, in contrast to study 3. Participants had a range of expertise relating to rivers and dams, from landscape design to group-based negotiation, fish biology to systems dynamics modeling. Our researcher participants did, however, have a solid background on MCDA, because we had been working together as a Future of Dams research team for two years. The workshop was a testing ground for the first (Excel macro-based) version of the DDST (section 5.2.2.1) and was designed to take 5 hours with refreshment breaks and dinner, which ultimately shortened active time to 4 hours.

A week before the workshop, participants received a digital packet of materials (a Google Drive folder, Appendix K, section 1) via email, along with a pre-survey (Appendix L, section 1). The participant packet included a materials summary document with agenda, DamDecisionSupport.xlsx file, instructional slides to be used in the workshop, an instructional video (explaining the AHP model using a car purchase example, and explaining the MOGA and the underlying concept of Pareto optimality using a cartoon example of production possibility frontiers, curves depicting the set of 'most optimal' decision alternatives for a watershed), as well as a Decision Scenario Description (document describing the purpose of the study, watershed-scale decision making, and the individual/group instructions for DDST 1), AHP methods document, consent forms, and pre-survey. Participants were asked to read the packet of materials to prepare for the workshop activities, fill out the consent forms or email with questions about their participant rights, and respond to a pre-survey. Because few participants responded to the pre-survey ahead of time, participants were asked to respond to an online pre-survey during the first 20 minutes of the workshop, where they were asked questions regarding their preferences for spending public tax dollars on different dam decision alternatives, preferences for decision factors (criteria), and whether or not they reviewed the digital packet of materials (Appendix K, section 1). After the pre-survey, participants were given an instructional presentation on MCDA and MOGA to generate a series of "efficient" multi-dam scenarios in the watershed and identify optimal decision alternatives at each dam using decision maker preference information from the MCDA. For all activities in the workshop, participants were asked to consider dam decisions on a watershed scale with no specific information about individual dams in the watershed.

Individuals were asked to download the Microsoft Excel AHP model to their own laptops that they brought with them (Excel was installed on University-provided and Windows-partitioned laptops for Mac users) and enable Macros upon opening the program file. Participants were asked to consider the entire Penobscot Watershed and were given specific directions for how to use the DDST. The individual DDST activity was followed by a 'pair share' (i.e., a discussion in pairs about individual results) and a presentation of anonymous individual results (including the mapped MOGA-MCDA outcome). The discussion about individual results led to a short debrief about how the individual DDST experience went. Participants were asked to share anything they learned or any challenges they encountered in using the tool. After breaking for a meal, participants worked in groups, where they were asked to discuss shared preferences to use with the DDST. The group deliberation was loosely facilitated by 3 researchers, each of whom sat at a table with a student group, answering questions, taking notes about key issues or themes in student conversation about the DDST (or dams in general), and providing guidance as needed. Group deliberations were also observed by 2 other researchers (both of whom, in addition to the 3 facilitating researchers, took detailed notes about the flow of conversation), participants discussed their individual results and came up with different negotiation strategies (depending on the group) to identify shared preference values for all 126 pairwise comparisons. While negotiation strategy was left open-ended as a matter of design, most groups chose to vote to speed up the process. After the group activity, we transitioned immediately into the debrief discussion where participants offered feedback about the user experience. Participants were emailed a post-survey link after the end of the workshop, to solicit private feedback about the facilitation, model mechanics, and overall workshop experience.

5.2.3. Study 2 Design

For study 2, the decision scope was narrowed from the Penobscot Watershed scale to 3 specific FERC-licensed hydropower projects in the main stem of the Penobscot River: West Enfield, Medway, and Ripogenus. The research team also generated additional forms of support for participants for workshop 2: dam factsheets and site-specific data for each dam. Each of the 3 projects has an upcoming relicense date in the next decade and is composed of only a single dam. Although there is a set of hydropower dams (Penobscot Mills Project, a series of 5 developments under a single FERC license) between Medway Dam and Ripogenus Dam, it was excluded from the decision context due to timing concerns and to simplify the process and time-commitment further for participants, based on feedback from Study 1.

5.2.3.1. DDST 2: 3-Dam WS MOGA-MCDA with R Shiny UI & Google Sheets Support

As with DDST 1, the UI and MOGA-MCDA portions of the DDST 2 were designed separately, as two parts of a whole. In DDST 2, AHP pairwise comparison-based preference elicitation was replaced with direct elicitation of preferences in the UI for the WS aggregation of criteria and preference data in the MOGA-MCDA. Unlike AHP and some other forms of MCDA, WS is an aggregation calculation and does not prescribe a specific preference elicitation method, so the researcher has freedom in how to collect preference information from users (in our case, direct preference elicitation). WS is a classic approach to MCDA, a decision support framework that handles DM preferences in a simple and easy-to-explain way. WS is "the most commonly used approach in sustainable energy systems" decision applications [35], likely due to the ease of calculation and interpretation. Many other types of MCDA (e.g., AHP, as in DDST 1) rely on WS to aggregate DM preference weights and criteria data to produce a ranked outcome. Some additional advantages to WS are: a) clear methods for calculation (i.e., simplicity, which was the driving factor in our decision to switch MCDA approaches); b) DM preference values need not be standardized in WS MCDA (as we opted to do through AHP in DDST 1); and c) opportunity for direct preference elicitation. These advantages (supported by an in-depth assessment in Ch. 4) motivate our use of WS in a participatory workshop setting for dam decision support.

Like the UI for DDST 1 (based on the watershed-scale decision scope, with no site-specific information), the UI for DDST 2 was designed to be general and not specific to any single dam. The goal for DDST 2 was to create a tool flexible enough to be used with multiple dam contexts, so while the MOGA-MCDA included site-specific data for optimization and WS aggregation and ranking calculations, the UI did not include specific dam references in preference elicitation for individual criteria. Instead, students were given instructions to think first about West Enfield Dam, then about Medway, and finally about Ripogenus when going through the DDST 2 activity. The number of decision criteria (from 6 to 12) and alternatives (from 7 to 5) also changed. Our research team elected to combine all hydropower decision alternatives (e.g., upgrade turbines, install additional hydropower capacity) into a single "improve hydropower" alternative. We also expanded the set of decision criteria (Table 27) to include annual electricity generation (MWh), annual carbon emissions reductions (tonnes CO_2), and the following 4 social criteria: indigenous cultural heritage (later renamed indigenous cultural traditions and lifeways, after member-checks with tribal project partners involved in related research), town/city identity (later renamed community identity for Study 3 and then later renamed back to town/city identity based on stakeholder feedback), industrial historical value, and aesthetics (defined in Table 27). The social criteria came from my analysis of stakeholder interview data (section 5.2.1.1.), but the data for the criteria came from student participant surveys. Student participants were surveyed ~2 weeks prior to the March 2019 workshop regarding the importance of the different social decision criteria for each decision alternative in Likert-style questions about each individual dam (Appendix L, section 2.0). For example, students saw the following question: "If the following decision alternatives happen, how do you rate the protection or preservation of AESTHETICS at the WEST ENFIELD DAM? Check one box per row." (Ratings range from 1 = no protections, to 5 = strong protections). Aesthetics was defined at the top of the multiple choice question as "a rating to convey the importance of the decision alternative for improving or preserving aesthetics (e.g., appearance, scenic value, smell, sound)", and the decision alternatives were likewise defined (e.g., "**Keep and Maintain Dam:** this is the do-nothing option, where the dam remains in place and minimal costs are incurred to ensure dam structural integrity and safety compliance"). The student data about the importance of social criteria for each decision alternative at each dam were then averaged, and the non-weighted mean survey data were used in the Dam Data Tables to support the individual and group DDST activity, as well as in the MOGA-MCDA itself (i.e., in the same way that we used calculated data for CO_2 emissions reductions, we used social criteria importance data for the social alternatives at each dam).

We selected a direct, compensatory preference elicitation method to use with WS: DMs were asked to move slider bars to indicate their quantitative preference for each decision criterion for each decision alternative and dam, making sure that their total preference ratings for all decision criteria under each decision alternative summed to 1. In this way, the DM self-standardized (set criteria preference values relative to one another) as they entered the ratings. Traditionally, WS aggregates DM criteria-specific preference values (compare these with the global weights from AHP) are with normalized criteria data (Eq. 71), where ***W*** is a weights vector of individual preference values (criterion preferences sum restricted to 1), matrix *[Y]* is the preference weighted criterion score matrix, and ***Z*** is the vector of aggregated (sum-product) criterion scores specific to each decision alternative (e.g., z_1 *to* z_m). Finally, decision alternatives are ranked (Eq. 72). As in AHP, the WS ranking is cardinal (though it is not usually interpreted that way because there is no true meaning inherent in one score that is twice as large as another). Like the Excel UI for AHP preference elicitation in DDST 1, the DDST 2 UI was designed solely for preference elicitation. The scalar preference vector output from the UI, ***W***, was the input for the MOGA-MCDA portion of the tool. Therefore, as with DDST 1, the WS calculation happened in the MOGA-MCDA, added on to the end of the pareto optimization. As in DDST 1, the MOGA optimization was based on the normalized dams data alone, before preference weights were added in the MCDA calculation. Once the Pareto optimal scenarios had been generated, the scalar preference vectors were used to weight the scenarios in a WS calculation, to select a 'first best' option from the optimal possibilities based on preferences. The MOGA-MCDA output was the scenario map of dam-specific decision alternatives.

Our DDST research team's observations and direct feedback (in workshop and post-survey) from Study 1 participants influenced the decision to shift from Microsoft Excel to R/Shiny software [224], [234]. The shift in UI software for DDST 2 was prompted by: a) user complaints; b) program hiccups with the

Excel Macro-Enabled Workbook; and c) R is free, open access, and open source and can work with any device that can access the internet. R/Shiny allows users without R experience to interact with a responsive, online UI http://shiny.gsscdev.com/dams_mcda/) to elicit user preferences in a clear, user-friendly way in DDST 2. The app provides a simple interface with directions (Figure 30) and supporting information to help the user directly rate criteria with slider bars on a 0-1 scale (as seen in Mustajoki et al. [59], Figure 31). An error message reminds the user that all ratings must sum to 1 for the aggregation and ranking to work. Based on Study 2 student feedback, the 0 – 1 scale was later transformed to a 0 – 100 scale for ease of interpretation. In DDST 2, we increased the total number of questions from 126 to 180 (i.e., 3 dams, 5 decision alternatives*12 decision criteria). This increase in questions was connected to an increase in decision alternatives (from 6 to 12) and because asked about each criteria-alternative pairing separately to maintain the thorough preference elicitation that we had been able to achieve in AHP. To achieve this, we redesigned the UI. In DDST 2, decision criteria preference elicitation was separated by decision alternative (opposite of the approach used in DDST 1), where each tab of the model qualitatively describes potential changes to various decision criteria specific to the decision alternative selected. Participants were asked to repeat the entire DDST 2 for each of the 3 dams. To support them in the individual preference elicitation activity, the research team focused on developing site-specific support materials (Appendix K, section 2) for each dam in the set of 3 (West Enfield, Medway, Ripogenus): Dam Factsheets, document describing decision criteria and alternatives, and Dam Data Tables. The results from DDST 2 were downloadable Excel spreadsheets with student preference information, which students were asked to refer to in the workshop (section 5.2.3.2.). As in Study 1, the MOGA-MCDA output was a custom map of the Penobscot Watershed, showing the top decision alternative at each dam site identified in the ranking step.

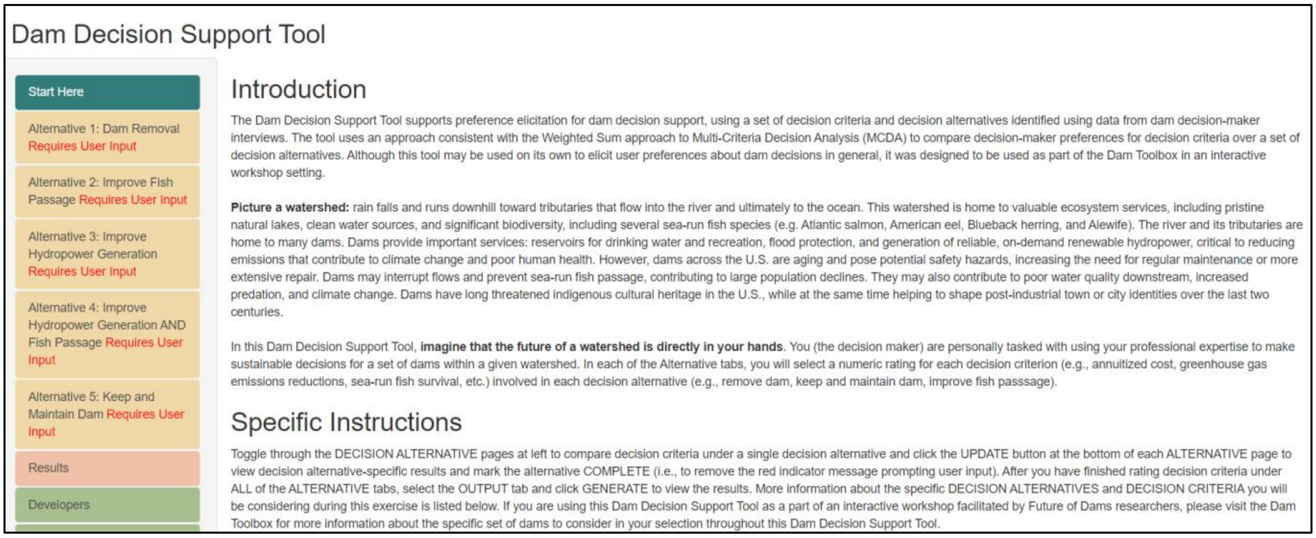


Figure 30. DDST 2 UI: decision alternative tabs to guide user.

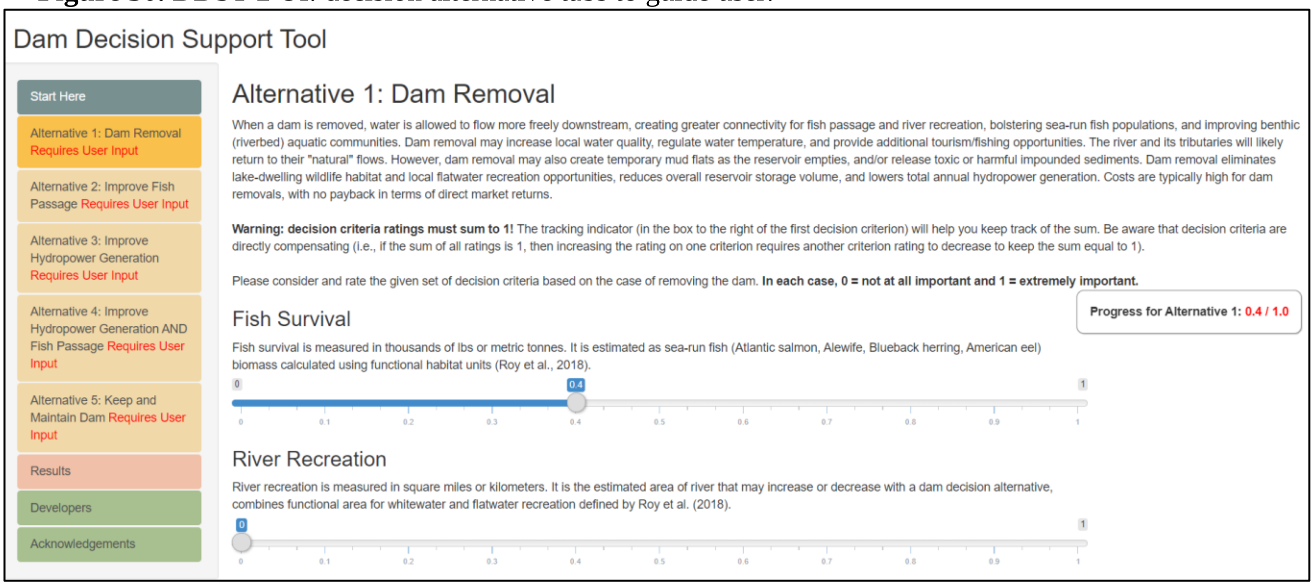
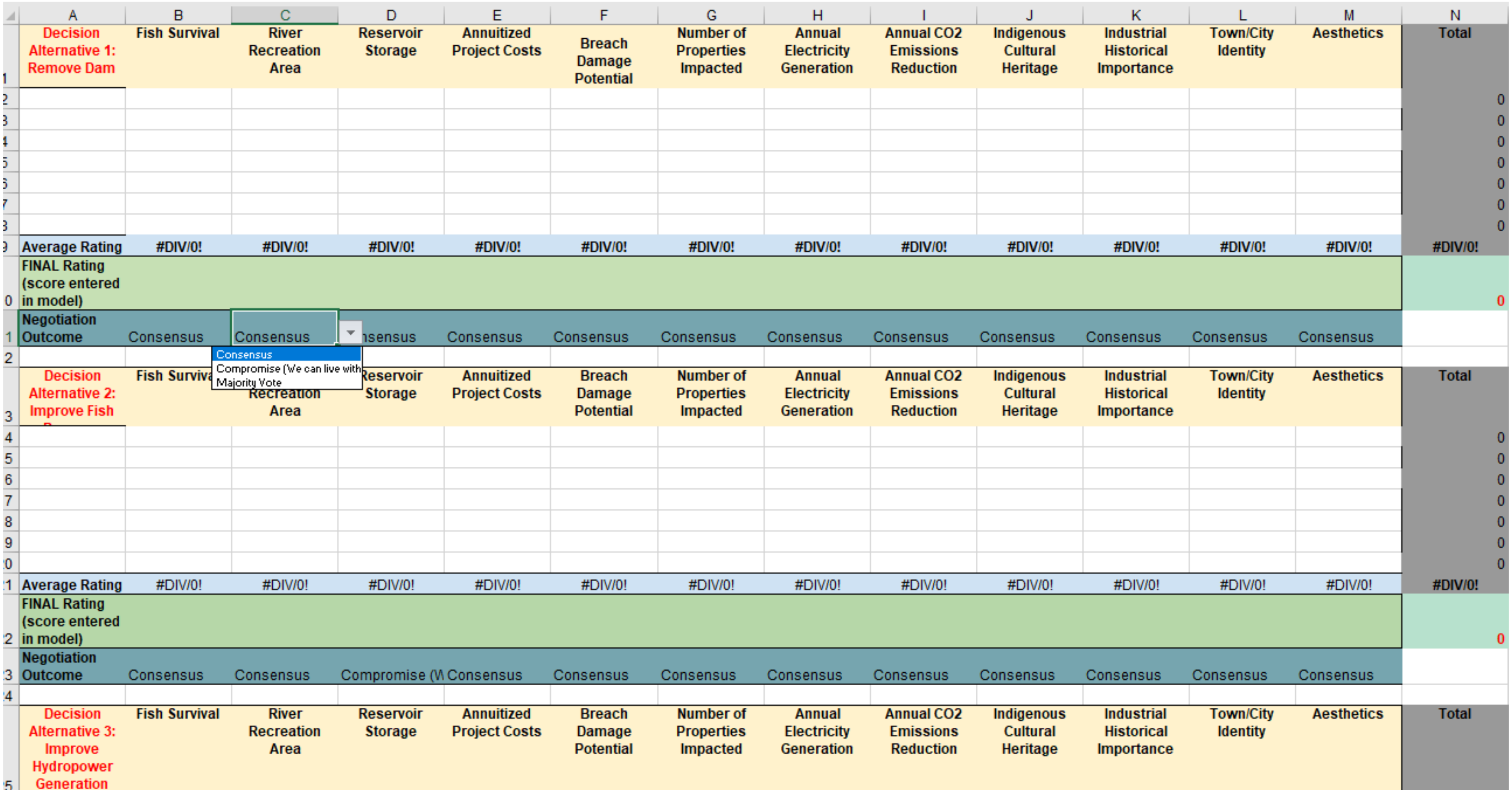


Figure 31. DDST 2 UI: Slider bars facilitate direct user preference elicitation on a 0 – 1 scale. A progress tracker helps keep the sum of decision criteria preference values equal to 1.

For the group activity portion of workshop 2 (Section 5.2.3.2), we asked groups to enter their DDST results into a Google Sheet (Figure 32), shared in a group-specific Google Drive folder (where their mapped results would be deposited after Roy ran the MOGA-MCDA model in Matlab). Individuals were asked to add their name, alias, or some other indicator (i.e., student 1, student 2) under the decision alternative, and their criteria scores for the decision alternative in their specific row. The total column kept track of criteria scores (participants were asked to make sure they summed to 1 for each row), and the non-weighted average rating for each criterion was calculated automatically. The idea was that groups could use the non-weighted average value as a starting point for negotiation over shared preference values. Groups were instructed to start the group negotiation conversation with a gut-check: did the average value seem like an appropriate reflection of shared values? The final preference rating (reflective of shared preferences) was to be determined by negotiation. Groups were asked to report their strategy for determining each criterion rating using a drop-down menu (options included: consensus, compromise, and majority vote). As in the individual DDST activity, students had access to the set of support materials (e.g., Dam Factsheets, Appendix K).



	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Decision Alternative 1: Remove Dam	Fish Survival	River Recreation Area	Reservoir Storage	Annuitized Project Costs	Breach Damage Potential	Number of Properties Impacted	Annual Electricity Generation	Annual CO2 Emissions Reduction	Indigenous Cultural Heritage	Industrial Historical Importance	Town/City Identity	Aesthetics	Total
2														0
3														0
4														0
5														0
6														0
7														0
8														0
9	Average Rating	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
10	FINAL Rating (score entered in model)													0
11	Negotiation Outcome	Consensus	Consensus	nsensus	Consensus	Consensus	Consensus	Consensus	Consensus	Consensus	Consensus	Consensus	Consensus	
12														
13	Decision Alternative 2: Improve Fish	Fish Surviva	Recreation Area	Reservoir Storage	Annuitized Project Costs	Breach Damage Potential	Number of Properties Impacted	Annual Electricity Generation	Annual CO2 Emissions Reduction	Indigenous Cultural Heritage	Industrial Historical Importance	Town/City Identity	Aesthetics	Total
14														0
15														0
16														0
17														0
18														0
19														0
20														0
21	Average Rating	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
22	FINAL Rating (score entered in model)													0
23	Negotiation Outcome	Consensus	Consensus	Compromise (W	Consensus	Consensus	Consensus	Consensus	Consensus	Consensus	Consensus	Consensus	Consensus	
24														
25	Decision Alternative 3: Improve Hydropower Generation	Fish Survival	River Recreation Area	Reservoir Storage	Annuitized Project Costs	Breach Damage Potential	Number of Properties Impacted	Annual Electricity Generation	Annual CO2 Emissions Reduction	Indigenous Cultural Heritage	Industrial Historical Importance	Town/City Identity	Aesthetics	Total

Figure 32. DDST 2 UI: Group discussion data tracking Google Sheet.

5.2.3.2. Workshop 2: March 2019 UMaine Students

In Workshop 2, which took place in March 2019, 35 students in a 400-level University of Maine undergraduate energy class tested the DDST and workshop format (updated with learning from Study 1) as an in-class activity to help them learn about MCDA. While student participants had no practical experience in dam decision making, participants were students in an interdisciplinary energy economics class required for multiple majors and minors, who recently established background knowledge on renewable electricity generation (including hydropower) and environmental sustainability issues with energy generation (including climate change). Students did not necessarily have specific dam knowledge, but some students (e.g., those with environmental majors) seemed to have a good background on migratory fish issues and river hydrology (e.g., dams create reservoirs, dams impact water quality downstream).

Two weeks before the workshop, participants filled out a pre-survey (Appendix L, section 2), as part of their weekly homework assignment, to generate qualitative (i.e., social) decision criteria data for the site-specific Dam Data Tables and the MOGA-MCDA portion of the DDST 2. During the week prior to the workshop, students received a second homework assignment (Appendix K, section 2.1.), accompanied by a Google Drive packet of materials (including the Dam Data Tables, Dam Factsheets, and background information about the Penobscot River), and a link to the DDST 2. Students were asked to perform the individual MCDA by themselves (making judgments about numerical preference values for decision criteria at each of 3 hydropower dam projects), time themselves during the activity, take notes on the experience of using the DDST, take screen captures of their results, and upload their decision matrices (populated with preference values) to a Google Drive folder. The support materials were intended to ground the decision context and support student users in preference elicitation, so students were asked to reference these materials (especially the Dam Data Tables and Dam Factsheets) during the individual at-home MCDA activity. The individual preference elicitation had to occur outside of class because there was not enough time in-class for the individual and group activities. Student notes about DDST 2 use during the homework activity served as a new, unique form of data gathered during Study 2.

After the homework due date (and in preparation for the workshop), I pulled together individual student results and averaged them for Samuel Roy, who entered the data into the MOGA-MCDA and created an example map of multi-dam class results for the workshop presentation. The students did not interact at all with the MOGA-MCDA during the individual activity; their first encounter with the mapped MOGA-MCDA output was on the day of the workshop. During the 3-hour workshop at the University of Maine, researchers presented a Powerpoint presentation on WS MCDA, as well as a general introduction to general MOGA operation using the same PPF slides from Study 1. The presentation included sample data tables for each step in the MCDA calculation (data collection, normalization, preference elicitation, preference weighting of normalized criteria data, and final ranking) to illustrate in a transparent way what was happening at each step in the process. Researchers instructed students on the UI and MOGA-MCDA mechanics (i.e., optimization using production possibility frontiers and Pareto efficiency) and shared the example map generated by the MOGA-MCDA to give students expectations for what would come out of the group negotiation activity.

During the group negotiation activity, students were divided into 6 groups of 4 – 6 students each and self-assigned individual responsibilities: modeler, facilitator, note-taker, data entry specialist, and reporter (with role variation based on group size as appropriate). Because student groups took notes on their negotiation process and challenges/opportunities for improvement encountered therein, a second unique form of data was generated for this activity. Students entered their own individual preference data into the shared Google Sheet (Figure 32) to calculate an average of individual scores as a starting point for a group negotiation. As they entered the data, they were instructed to share their preferences verbally with their group, one dam-decision alternative decision matrix at a time, and to have a group discussion about: 1) how similar/different their individual results were; and 2) whether the average of individual preferences was sufficient for capturing the group's preferences or whether (and how) it should be adjusted. Once the students had completed their group negotiation about this second topic, they were asked to identify in the Google Sheet whether they arrived at the decision via a) consensus, b) compromise ("we can live with it"), or c) majority vote. Participants entered final group responses for each decision criteria-alternative pairing into the DDST and uploaded the resulting decision matrix to a Google Drive folder for researchers to use as input to the MOGA-MCDA. Researchers (one researcher per group) observed the group negotiation, took notes, and answered clarifying questions as needed, loosely facilitating the discussion. In each group, there was a self-assigned student facilitator did most of the discussion facilitation, instructed at the start of the workshop by their teacher (Dr. Klein) to keep the conversation moving, help identify potential areas of compromise or consensus, and make sure each student in the group had a chance to share their opinion. These roles and instructions were not new to the students, as the course had already been taught for nearly two months through an active-learning approach that involved many regular discussions like this with similar self-identified student roles.

The group negotiation process took much longer than expected, despite the fact that groups used the averaged individual preference values (from their homework individual DDST activity) as a starting place for discussion. Our research team originally planned to do the entire group negotiation for the three dams (West Enfield, Medway, Ripogenus) in one class session, but we extended the workshop into a second day (a week later) to both give student groups a chance to finish their discussions about shared preferences at each dam, see the mapped MOGA-MCDA results from the previous week, and then debrief the group activity and results. In the debrief, student groups shared some of the observation notes they took about themes in their own groups' discussions, and students were able to comment on these themes, as well as individual vs. group experience, the online UI, and the MOGA-MCDA mapped recommendation. While we did explain how MCDA works, individuals and groups did not get to see their site-specific ranked decision alternatives or scores; rather, groups only saw the optimal decision alternative for each site, based on a multi-site optimization (the MOGA-MCDA).

5.2.4. Study 3 Design

In Study 3, added to the dam set the Penobscot Mills Project, a series of 5 dams, 4 of which are operated as a unit under the same license, (ordered by latitude): East Millinocket, Dolby, North Twin, Millinocket/Quakish, and Millinocket Lake Dam (non-powered). Based on student feedback, we eliminated the fatigueing and unnecessary decision alternative-specific preference elicitation and structured the UI preference elicitation tabs by dam, so it would be easier for the user to use the tool for the full set of dams at one time, rather than reloading the tool repeatedly for different dams as they had to in DDST 2. We deemed the decision-alternative-specific preference elicitation unnecessary because across Studies 1 and 2, we had seen little evidence that users had sufficient variation in preference for decision criteria across different decision alternatives to make the extra time and effort on the part of the participant (and researcher) worthwhile, but there was sufficient evidence that preferences could vary substantially across different dams. With the expansion to 8 dams and elimination of decision alternative-specific preference elicitation, the user now only had to make 96 decisions in their preference elicitation (8 dams*12 decision criteria) as opposed to 126 in Study 2 and 180 in Study 3.

In addition, we streamlined the instruction text and added a tab with an interactive map of all 8 dams, including hover links to highlight key site characteristics (e.g., power capacity). In the development of DDST 3, the decision matrix was reviewed by DMs in a member-checking focus group before Study 3, where a group of engaged stakeholders, alongside the research team, determined that public health and socio-environmental justice should be added to the list of decision criteria (these were subsequently removed from the version that is being prepared for public release, after Study 3 participants observed they created a false dichotomy in DDST preference elicitation, see section 5.3.3.). The set of decision alternatives was unchanged between DDST 2 and DDST 3. Finally, our experience in Study 2 and an ongoing review of the literature (Ch. 4) informed our switch from a generic DDST that required substantial time and effort by the researcher and participant to manually enter data and perform calculations for the group activity, to a streamlined version of the tool with 'individual' and 'group' modes, along with the capability to upload a csv file with predetermined preference values (making researcher and participant review and editing of previously entered preference values much more time-efficient and easier).

5.2.4.1. DDST 3: 8 dams WS with R Shiny UI

Unlike previous versions of the DDST, the UI and WS MCDA model (no MOGA) are fully integrated in DDST 3. DDST 3 has several other functional and organizational changes when compared to

DDST 2. First, in response to critiques about DDST 2, DDST 3 has more straightforward instructions, navigation, and an advanced app structure. DDST 3 includes navigation buttons (Previous, Next), simplified instructions (Study 2 participants suggested that less text and a more intuitive UI would improve user experience), distinct options for individual and group use, and a preference file upload option for familiar and repeat users (Figure 34). DDST 3 also includes new architecture for users to log in as part of a group and, in this mode, the tool automatically averages individual responses from each group member anonymously in the back end of the model). The tool also automatically sets the slider bars for each dam page at the group average, as a visual support to more efficient group negotiation. Second, in another departure from the generalized structure of DDST 2, DDST 3 has been reorganized around the site-specific dam context, including an interactive map (Figure 35), which marks the 4 hydropower projects (8 dams) coming up for relicensing in the next 10 years in the Penobscot River watershed that participants considered in Study 3. DDST 3 includes separate pages for direct, dam-specific criteria preference elicitation (again using slider bars: http://shiny2.gsscdev.com/), separate results pages for individual dams and a coordinated, multi-dam results page (a recommendation based on top decision alternatives from each single dam MCDA). Third, building on these ideas of a more intuitive UI and site-specific reorganization, DDST 3 includes additional in-app resource links (Figure 34; for users who want more detailed information, and for all of the support materials previously included in Study 2 via a separate Google Drive folder to be now directly at the user's fingertips), including Dam Factsheets, Dam Data Tables, a relevant peer-reviewed journal article about multi-dam scale decision-making in the Penobscot River watershed (Roy et al. [18]), and instructions about how to use the tool (aimed at improving the model's shelf-readiness. Fourth, tying in with the shelf-ready preparations, we designed the online DDST 3 so that MCDA calculations were brought to the forefront in the UI: decision criteria data are normalized and combined with user preference information after the user to enter preferences directly, using a 0 to 100 scale (a change based on suggestions from participants in Study 2, who struggled with interpreting the 0-1 scale in terms of percentages). Also, and again in response to participant critiques from Study 2, the individual dam results pages show the MCDA-based recommendation and break the results down step-by-step in an effort to improve transparency about how the MCDA calculation worked. This is achieved through a series of tables, moving from user preference information and site-specific criteria data to normalized criteria data and preference-weighted normalized criteria data. Fifth and finally, DDST 3 includes new options for downloading data including user preference information, tables of results, and graphed individual and multi-dam results.

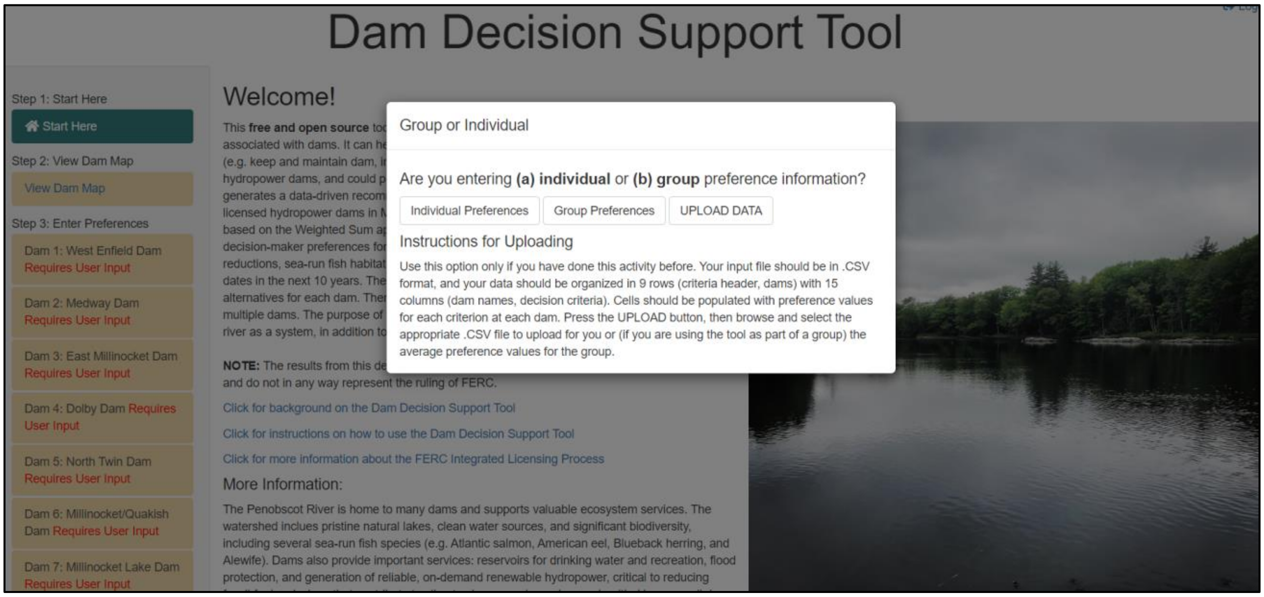


Figure 33. DDST 3 dialog box asking the user to select individual or group preferences or upload a preference data csv file.

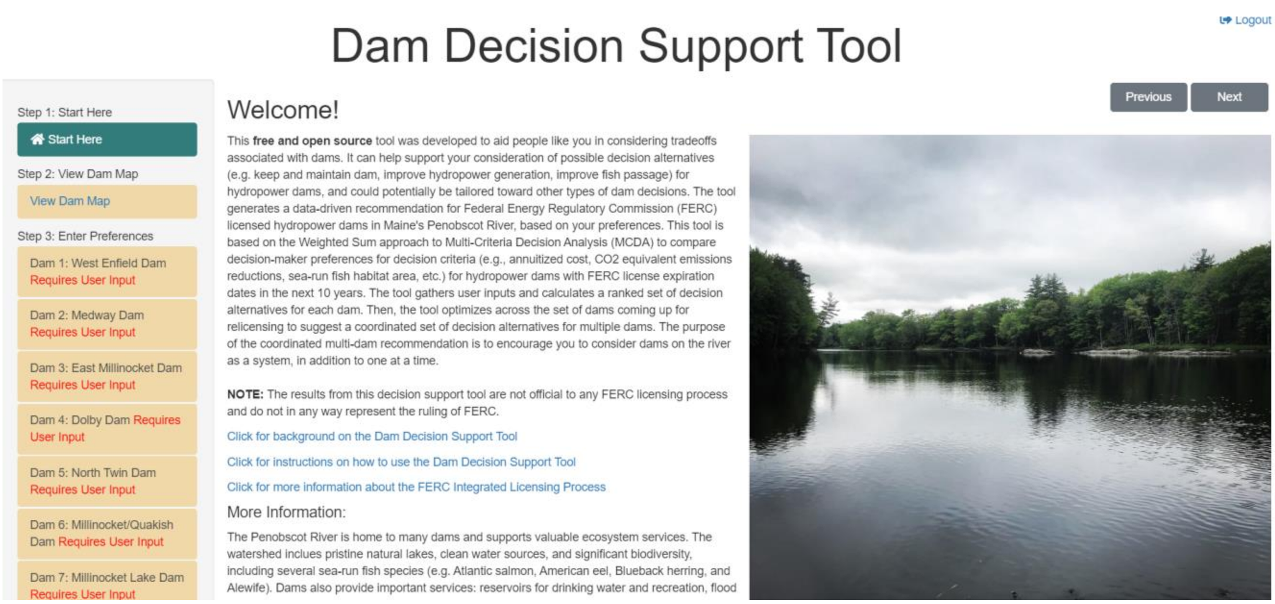


Figure 34. DDST 3 UI with instructions, links to additional resources, new navigational buttons (upper right: Previous, Next) and dam-specific tabs (left; in contrast to the alternative-specific tabs in the DDST 2 UI).

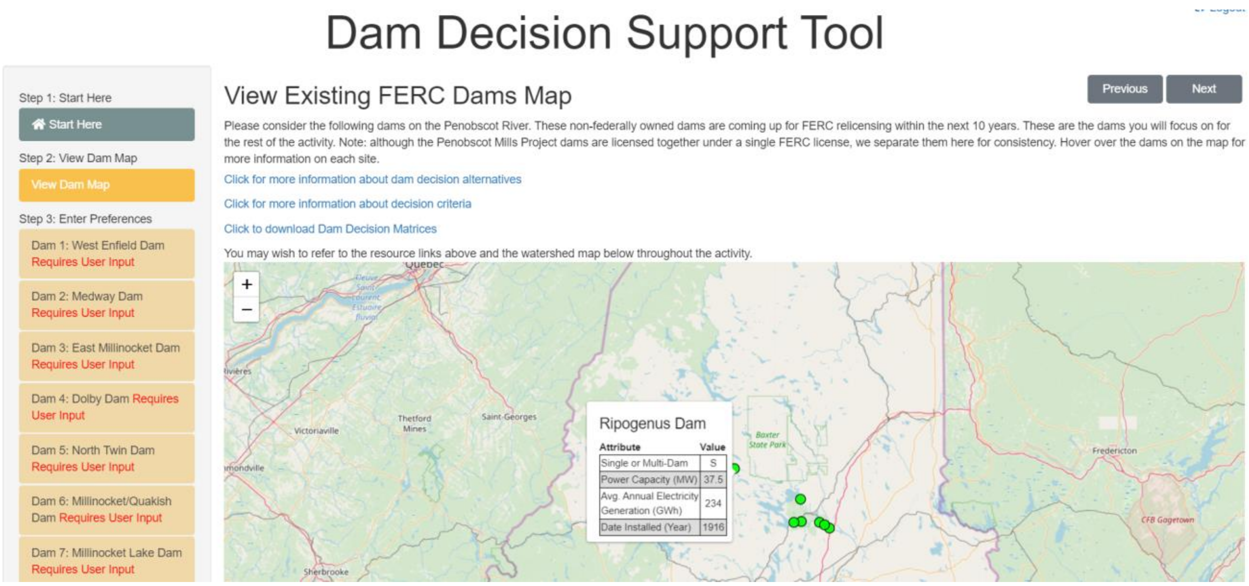


Figure 35. DDST 3 with a map and site-specific data to orient users to the decision context.

As with DDST 2, the DDST 3 weights normalized decision criteria data by user preference values, calculating the weighted summed score, ranking the decision alternatives by highest to lowest score. Unlike DDST 2, DDST 3 does this MCDA calculation within the UI (in DDST 2 the UI was strictly focused on preference elicitation for the MOGA-MCDA, which was external to the online interface) and also generates a series of results tables and graphs to support user interpretation of outcomes. DDST 3 does not include the MOGA multi-dam pareto optimization calculations because, despite a year's effort to try to completely integrate the MOGA and new DDST MCDA UI design to work seamlessly as one cohesive user-driven model with automated (as opposed to manual researcher-driven) results, full integration with accurate results and validation was not achieved by the time of Workshop 3. More specifically, we experienced multiple calculation errors but did not have time before Workshop 3 to fully troubleshoot whether the issue was a map numbering error (i.e., the MOGA was not linking to the correct mapped output, based on the MCDA results) or something else. The DDST team made changes down to the final day before the stakeholder workshop and ultimately decided in the final hour to exclude the MOGA from the MCDA procedure to ensure Workshop 3 participants would have a complete result that would be accurately calculated, understandable, and clear. However, the MOGA was used to produce average river recreation area and sea-run fish habitat area criteria data used in the DDST 3.

To facilitate the ‘group mode’ function, our DDST research team’s software engineer enabled a login process using Django [235] to augment the existing Shiny app. When individual users ‘sign up’, they create an account and associate their preference elicitation activity with a specific group (group numbers pre-loaded by a DDST programmer and selected by the new user from a dropdown menu). DDST 3 automatically and anonymously aggregates the individual preferences the users select while in “Individual” mode with other individual group member preferences. When the user refreshes the app and selects to group instead of individual mode, they will see the slider bars have been automatically set at the non-weighted average preference rating for the group (where, in contrast, in individual mode, the slider bars were set equal to 0 at the start). This group mode functionality was inspired by Simonovic and Bender [58], who offer similar functionality in their decision support tool, called a Collaborative Planning Support System (CPSS). As individuals use the CPSS to identify decision criteria, they can simultaneously see the criteria that have been selected by others in the group (criteria are depicted anonymously).

5.2.4.2. Workshop 3: October 2019 Dam Stakeholders

The purpose of Workshop 3 was to ground truth (i.e., with real DMs) DDST 3 in individual and participatory group settings and for single and multi-dam decisions. Unlike the previous two studies, the research team invited dam stakeholders and dam decision makers in Maine to attend the workshop at the University of Maine. All 9 participants, identified through stakeholder interviews and snowball sampling (where interviewees mentioned other groups we should reach out to in the FOD research), were invited because they represent groups with some interest in the identified 8 dams coming up for relicensing (either personally or professionally). Our research team targeted these groups as a representative cross-section of the kinds of groups historically involved in Maine dam decisions, and selected potential participants based on their participation in stakeholder interviews and snowball sampling (where interviewees identified other key groups involved in dam decision making). DM participants included a U.S. federal agency representative, tribal nation representatives, and a Maine state agency representative, while stakeholders included tribal nation citizens, a private sector company, an international non-profit organization (NGO), and a state-level non-profit organization. Our research team sought to balance participation across the diverse set of interests represented in hydropower dam decision making, so we were intentional about our invitations and numbers, attempting simultaneously to keep the group small (with negotiation discussions in mind) and balanced in terms of perspectives broadly representing hydropower interests, fish interests, tribal interests, and town/city interests.

Despite multiple outreach attempts, no town/city officials or dam owners were represented in the workshop; however, the private sector company representative understood dam owner or hydropower interests. Participant knowledge of the set of 8 dams was extensive—every participant was familiar with the dam locations, the licensee, and the general set of issues surrounding each dam. Most (>50 percent) of the participants had been involved in dam decisions previously in the State of Maine (at some level, whether as an official legal representative of a group, acting on behalf of a group in submitting public comment, or in submitting official regulatory permitting/prescriptions for the dam), a change in experience level from researcher and student participants. Two months prior to the workshop, relicensing for one of the dams being considered in the workshop, West Enfield, had officially begun. In fact, some of the workshop attendees had been at the site visit and scoping meeting for the West Enfield relicensing and planned to be involved in the full 5-year (or more) effort. It is likely that participation in the workshop was limited because the dam owner and other potential participants were not comfortable or felt that they could not discuss an active relicensing outside of the official FERC process.

Two weeks before the workshop, participants filled out a pre-survey. The workshop was 8 hours long, so refreshments (including muffins, juice, fruit) were provided and there were breaks for coffee and lunch. Most DM participants had been involved in the research at various stages: interview (for establishing decision criteria and alternatives), member-checks, and informal discussions (in person, phone, email) about this research, but many had not met each other. In addition to the Dam Factsheets and an improved version of the Dam Data Tables developed for Study 2 (Appendix K, sections 2.3., 2.4., respectively), the research team developed handouts describing the decision criteria and alternatives for quick reference throughout the workshop. The research team also created a series of posters describing the decision criteria and alternatives in greater detail (e.g., mathematical equations, citations). Posters were referenced in MCDA instruction and participants were welcomed to explore the posters during coffee breaks. As in previous workshops, the participants received a participant packet of information to support them in the workshop activities (e.g., Dam Factsheets, Dam Data Tables, Background Document, etc.). A facilitator (Sharon Klein, a member of the research team) led the bulk of the workshop and group negotiation activity, trading off with other researchers as appropriate for discussion or instruction.

Because not all participants had worked together before (though many had crossed paths in official capacities), we began the day with an ice-breaking activity, where participants 'speed-dated' (answering questions such as "what TV show are you currently binge-watching?") to learn about each other and establish personal rapport. Afterward, the researchers asked the group if they were willing to collectively agree to (or modify as needed) a set of process commitments; e.g., be respectful of others, moderate your own participation, and have fun (Figure 36). The process commitments were designed to create a safe space for participants to share ideas and learn. Process commitments also aided group facilitation when some participant voices threatened to drown out others.

Figure 36. Workshop 3 (Study 3) group commitments list recorded on large Post-it™ paper.

After we agreed to process commitments, the facilitator(s) gave an instructional Powerpoint presentation orienting participants to the dam decision scenario (e.g., 8 dams coming up for relicensing on the Penobscot River). In the introductory presentation, participants learned about the purpose of the workshop, as well as MCDA mechanics (including decision alternatives, and criteria), and were given an opportunity to ask clarifying questions. It is important to note that some of the participants (N = 5) had previously had an introduction to MCDA, during one or more focus-group sessions to co-develop an evaluative rubric for the workshop with stakeholders. The question-and-answer session may have gone on longer if so many (>50 percent) of the participants had not had a more substantial prior knowledge of MCDA. Researchers spent approximately an hour answering MCDA-related questions and clarifying decision criteria definitions and normalization procedures. At this time, I shared another folder in the participant packet Google Drive that included the publicly accessible peer-reviewed background reading that informed our estimation of decision criteria (e.g., Hall et al. [36], O'Connor, etc. [11], and NREL [152]), because it seemed that some participants were particularly engaged and curious to learn more about our methodology.

Before the individual activity, participants received a tutorial about how to use the DDST, including instructions about how to sign up and associate themselves with a group, in preparation for the group activity later in the day. Then, participants worked through the DDST individually (online, using provided laptops). After the individual activity, some participants ate lunch and discussed the morning's activities while others ate and finished up working through the individual activity. After lunch, the facilitator asked participants to recall the process commitments before working together as a group, where the lead facilitator (Klein) entered ratings as they were discussed into a laptop and projected on a screen for all to see. Participants performed the group negotiation activity in a single group of 9 people, facilitated by 1 researcher (and observed by 3 others). During the group negotiation, the facilitator logged in and selected 'group mode' to begin the guided discussion about shared criteria preference ratings, starting from the non-weighted average of individual criterion preference ratings automatically populated by the DDST 3. Recall that DDST 3 had a 'group mode' that aggregated individual preferences anonymously when group users each performed the activity in 'individual mode'. After the group negotiation process, the stakeholder participants debriefed about the experience. While we had instructed them to try to reach consensus as the goal of the negotiation, the actual process was somewhat different, where one of the participants ended up leading the conversation in a new direction. This participant-led negotiation was a primary focus of the debrief: how close was the process to reality? Did participants feel as though their compromises were something they could propose in the FERC relicensing space? We also asked participants to think about and reflect on their experiences in using the tool. The facilitator wrote feedback (as stakeholders were comfortable) on poster paper so that everyone could see (section 5.3.3.). After the debrief, we asked participants to fill out a post-survey while they were there. The post-survey was an important a way to capture participant perspectives about the DDST 3 and workshop activities that they may not have been comfortable sharing in front of others during the workshop debrief discussion.

5.2.5. Comparative Case Study Analysis

The MCDA results, post-workshop surveys, and researcher observations are the primary forms of evidence for this case study and provide links in the chain to establishing inference (Figure 37). Post-surveys provide a direct, individual-participant-level evaluation of the workshop activities, performance of the model, facilitation, and the overall workshop experience. I include text excerpts from post-surveys, student notes or group summaries from Study 2, and researcher notes where appropriate. I identify themes and patterns in participant questions, comments, and discussions recorded in researcher notes. These forms of evidence contribute to my analysis of post-surveys (adding depth and richness to my interpretation by supporting or contradicting participant post-survey comments). The open-ended participant feedback helps establish potential rival explanations for the data [222] by asking participants about whether they liked/learned from the activity or materials, and how they evaluate various other aspects of the workshops (including the DDST). In addition to the open discussion of rival explanations [222], the key to establishing research credibility is methodological adequacy (which I establish through triangulation of interpretations through peer-checks, and member-checks) [220].

Figure 37. Links in the 'chain of evidence' for this case study.

While there are many consistencies across the data sources that I use for my case study, there are a few key differences (Table 28). Study 1 individuals did not see post-survey questions aimed at cross-comparison. In that sense, Study 1 served as a useful pilot for workshop materials and activities, including the post-survey. Responses to the post-survey evaluation questions were particularly useful to the DDST research team in thinking about what to refine, adjust, or exclude from future versions of the tool, so we more than doubled the number of evaluation questions in post-surveys for Studies 2 and 3. We also found the Study 1 post-survey open-ended feedback questions to be helpful, because they reinforced what we had observed and recorded in our researcher notes, but in the participants' own words. This was a point of assessment that we retained for Studies 2 and 3. While we (myself included) recorded our researcher observations, the number of observing/note-taking researchers was not always consistent from study to study. In Study 2, students took notes of their own experiences using the DDST 2, and groups recorded summaries of their experience using the tool and agreeing on a shared set of preferences in the negotiation activity. I rely predominantly on direct participant feedback, whether through notes, open-ended post-survey feedback, and responses to post-survey cross-comparison questions here.

Table 28. Case study evaluation data comparison.

Data Source	Question	Study 1	Study 2	Study 3
Post-survey cross-comparison questions	Individual vs. group decisions? Why?	N	Y	Y
	Single vs. multiple dam decisions? Why?	N	Y	Y
Post-survey evaluation	Multiple	Q = 15	Q = 32	Q = 34
Post-survey open-ended feedback	Are there any other questions you think we should be asking in the pre- and post-survey	Y	N	N
	Please discuss anything, in particular, you learned from the workshop or anything you found interesting/worthwhile.	Y	Y	Y
	Please discuss any particular challenges or difficulties you encountered in the workshop.	Y	Y	Y

Table 28. (Continued)

Data Source	Question	Study 1	Study 2	Study 3
	Please discuss any suggestions for improvements to future workshops like this.	Y	Y	Y
	What additional information would you like to see in the Dam Factsheets, if any? How would this additional information improve your ability to make a decision about a dam?	N	Y	Y
	Other suggestions, questions, comments?	Y	Y	Y
My observation notes	NA	Y	Y	Y
Other DDST research team member notes	NA	R = 4	R = 3	R = 4
Individual MCDA Results (e.g., map, graphs)	NA	Y	Y	Y
Group MCDA Results (e.g., map, graphs)	NA	Y	Y*°	Y*

Abbreviations: Y = yes; N = no; Q = number of questions; R = number of researchers; NA = not applicable; *group negotiation over shared preferences started as the non-weighted average of individual criteria preference ratings that were then adjusted based on gut-check and discussion or voting; °individual MCDA results were combined via data entry from homework responses, and then a single individual in each group entered them into the web app.

The embedded 'test' studies incorporate direct individual model interaction and group deliberation over different types (single, multiple) of dam decisions, a 2x2 factorial design (Table 29). The first axis of comparison, individual and group MCDA components, was a common element in all embedded studies. I report the (a) summarized MCDA outcomes for individuals in each study and (b) MCDA outcomes across all participants in Studies 2 and 3 for the three dams they have in common: Medway, West Enfield, and Ripogenus. Note: participants in Study 2 did not all discuss every dam as a group (i.e., some groups ran out of time after identifying shared preferences for one dam), and participants in Study 3 did not deliberate about Medway or Ripogenus dams. For consistency in comparison, I use the dam-specific non-weighted average of individual participant preference values for decision criteria to calculate 'group' MCDA results, reported at the Study level (even though all groups in study 2 did not deliberate as a single group). I apply the dam-specific non-weighted average of individual preference values to the entire set of dams (despite study 3's group discussion being limited to West Enfield for the sake of time). In short, the 'group' results presented in this chapter for both studies 2 and 3 are somewhat manufactured; however, the averaged 'group' preferences deviate only slightly from the shared preference values established by actual groups (e.g., through negotiation or voting) in each study, because the non-weighted averages of individual preferences were used as a starting point for those discussions. Survey data were downloaded from Google Forms and re-coded using numerical values for analysis. All descriptive analyses (i.e., averaging individual preferences to proxy group preferences, summarizing survey data) were performed using Microsoft Excel or Tableau. In all cases, "does not apply" and null responses have been excluded from analysis. The small sample size limits statistical power, but I report significant results where possible.

Table 29. Axes of comparison for 2x2 case study design

		Type of MCDA Activity	
		Individual	**Group**
Type of Decision	**Single Dam**	Study 2, Study 3	Study 2, Study 3
	Multi-Dam	Study 1, Study 2, Study 3	Study 1, Study 2

Finally, I evaluate the embedded 'test' studies using the two dimensions from Chapter 4 (Model Complexity and Depth of Engagement, Figures 38 and 39) referring to the workshop post-survey feedback and researcher observation notes from each workshop to anchor my impressions. Recall, for a rating of 1 on the Model Complexity dimension, a model must be simple and straightforward enough for DMs to use it on their own, without the need for a researcher. As the ratings increase, models require knowledge of academic theories or advanced computational methods. At a rating of 5, the model is too complex for DMs to use without researcher support. For a rating of 5 on the Depth of Engagement dimension, a modeling process must include iterative group negotiation or discussion, with DM feedback into the model development itself. As the ratings decrease, modeling becomes less and less participatory, until it is a one-way input from stakeholders into the model via interview or survey (survey-based participation rates at 1 on the Depth of Engagement dimension).

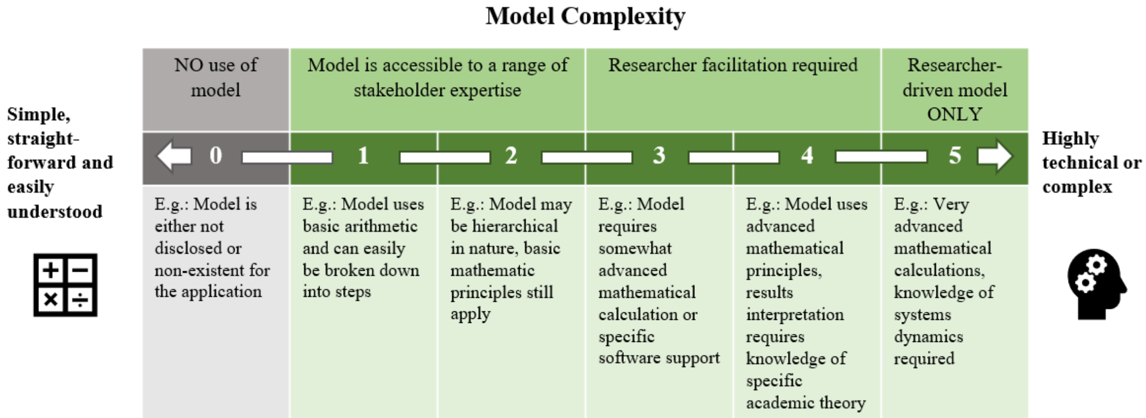


Figure 38. Model Complexity ratings used to evaluate DDSTs. Source: Ch. 4.

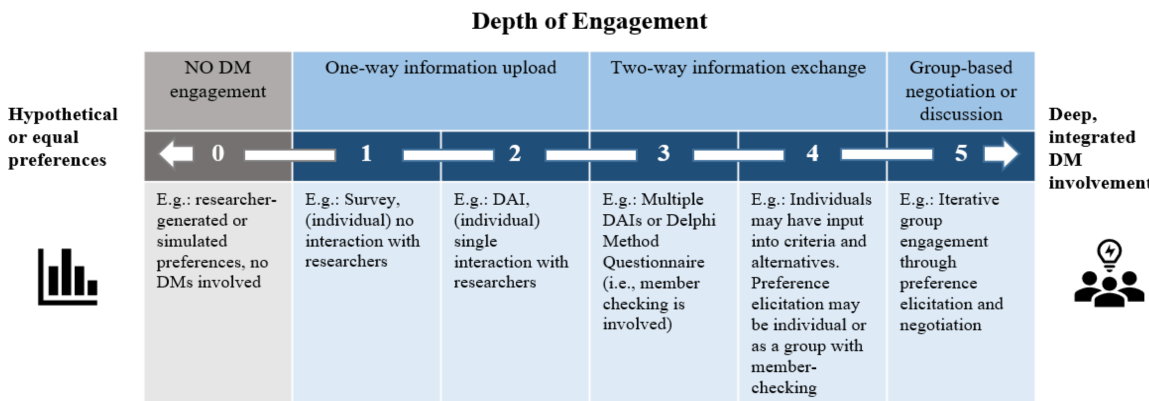


Figure 39. Depth of Engagement ratings used to evaluate stakeholder engagement (group and individual) with the DDST. Source: Ch. 4.

The two-dimensional assessment circles back to my previous arguments about the need for *ex-post* assessment, while the group/individual MCDA results, researcher observations, and post-survey results serve as links in the chain to establishing causal inference (see Figure 37 above) [222]. I trace the process of development using the embedded 'test' studies as waypoints for comparative analysis, considering the evidence at each link in the chain, ending with a comparative analysis. The set of three embedded studies help make the case about the role of DDST in enhancing *participatory capacity* through the user experience, while presenting a range of relevant information (decision criteria, alternatives, data, fact sheets), thereby providing *access to information*.

5.3. Results

In general, participant perception of the DDST, decision criteria, and preference elicitation process improved from Study 1 to Study 3 (Table 30). The MCDA model went from being perceived as a black box (i.e., the participants could not necessarily see what was going on or explore the calculations leading to the graphed recommendation output), to being traceable through a series of tables illuminating each of the steps from raw criteria data to normalization and aggregation/ranking. Criteria became understandable (though not necessarily transparent) as we learned from Study 1 and Study 2 participants what additional information or framing would support their understanding (sections 5.3.1. – 5.3.2.). The preference elicitation was something into which we put a considerable amount of time and effort developing a process that was both clear and user-friendly. We benefitted from having specific user feedback on those two points in Studies 1 and 2. Receiving feedback from participants that they needed more scientific data (Study 1) and more context for decision making at each dam site (Study 2) enriched the tool to the point where Study 3 participants did not express a need for more data (more discussion on this in section 5.3.3.). We were able to achieve 'believability' with our graphed preference results, but not the MOGA-MCDA result. The mapped MOGA-MCDA results were shown to participants in the context of their own preference inputs in Studies 1 and 2, but participants in both studies did not agree that the results were a representation of their preferences. In DDST 3, we ended up running out of time to fully integrate the MOGA into the UI alongside the MCDA, and ultimately dropped the MOGA model from the tool altogether. So, while participants also saw an example of mapped MOGA-MCDA output in Study 3 (the 'Keep and Maintain' decision alternative at each dam site), they did not seem to understand what the map was showing, and there seemed to be some general, shared apprehension about the map (not unlike what we observed in the first two studies). Finally, the group negotiation strategies were different across all 3 studies. While much of this can be attributed to time allowed for discussion and the actual focus of the negotiation (i.e., negotiation over shared preference ratings for just one dam in Study 3 as opposed to 3 dams in Study 2), having a dedicated facilitator, with intimate knowledge of the DDST and workshop goals, was an asset to the group participatory process (section 5.3.3.). I describe the study-specific results (e.g. participant post-survey feedback, researcher observations) chronologically to support a semi-narrative description of DDST development before delving into a cross-study comparative analysis (section 5.3.4.). Each subsection before the cross-comparative analysis ends with a summary of study-specific lessons learned.

Table 30. Comparison of qualitative study findings.

General Finding	Study 1	Study 2	Study 3
Criteria understandable?	N	N	Y†
Preference elicitation clear?	N	N	Y
Preference elicitation user-friendly?	N	Y‡	Y
More data needed	Y	Y	N
MCDA understandable?	N	N	Y
MOGA understandable?	N	N	NA
Model perceived as a 'black box'?	Y	Y	N
Graphed MCDA results believable?	N	Y	Y
Mapped MOGA-MCDA results believable?	N	N	N•
Individual and group modes?	N	Y°	Y
Dominating group negotiation strategy	Voting	Voting*	Compromise

Abbreviations: Y = yes; N = no; NA = not applicable; *****based on observation, as student assessment of the negotiation strategies used was inaccurate; †understandable, but not considered transparent due to the mathematical computation or understanding about the survey methods required to understand the criteria data; ‡ model is more or less user-friendly, could use some improvements; • = map shown with example 'Keep and Maintain' results at each dam site for context; °group 'mode' was in the form of an Excel spreadsheet, used to aggregate and average individual responses as a starting place for negotiation.

5.3.1. Study 1 Outcomes

The DDST 1 received much critique in both the MCDA activity debrief session and in the post-survey in Study 1. The research team also observed participant discomfort with the DDST 1. To begin with, participants seemed to feel that the decision criteria (as written) were not understandable. Several participants reported that the questions made them feel "quizzed" about the dam issues (decision criteria) rather than surveyed; they felt as if there were some right answer they were being asked to identify, rather than their own expert opinion. Participants expressed a need for clear instruction about how they should respond (e.g., with their own expert or personal opinions, or ‘wearing a certain hat’). Researcher notes about participant responses included several comments highlighting these tensions:

> **Excerpt from researcher notes on 6/4/18:** “Should you base answers on what you know or what the ‘right’ answer is?” This kind of question was raised multiple times…Some people said things along the lines of “it feels like a quiz. I don’t know which [decision alternative] is better for hydropower [generation].” This was a direct quote [from a landscape architect] and there were many questions similar to it.

Researcher participants made it clear that the decision alternatives by themselves were not enough to support their preference judgments. Different participants had different ideas about how different decision alternatives might impact the river, so many participants found themselves reconsidering their previous responses when it came to the group activity. The group activity seemed to cause additional confusion when participants were asked to work together to identify shared preferences. Some groups over-analyzed the decision alternatives, extending tradeoffs beyond the specified decision criteria to other, related criteria; however, it is important to note that our participants were academics, used to analyzing (and in some cases over-analyzing) one another’s work.

> **Excerpt from researcher notes on 6/4/18:** Butterfly effect - new turbines over dam removal can give households more money, which means less time needed working, which means a greater opportunity for recreation.
>
> **Excerpt from my reflection notes on 6/12/18:** Over-extrapolation→ if dams come out, households have more money, more time for recreation, etc. People spent too much time thinking about tertiary effects.

Participant attempts to break out of the pairwise comparison structure and consider secondary or tertiary effects appeared to be a way to try and gather information through extrapolation or projection. Attempts to consider secondary and tertiary effects only served to slow the process, rather than generate new information for participants to draw from. Groups that discussed the potentially far-reaching ripple effects of decision alternatives (e.g., new turbines resulting in more household income due to lower costs of electricity from increased hydropower generation) quickly found themselves hung up on regional economic considerations. This type of researcher observation (e.g., participant entanglement in ripple-effect thinking for tradeoff decisions), as well as post-survey comments, suggest that participants needed additional description of each decision alternative to support them (and bound them) in the group activity. One participant responded to the post-survey saying:

> *"It was hard to learn more about the alternatives when we didn't have any more information than we started with. There was a lot of confusion between PREFERENCE vs what we thought was the best alternative based on our best available knowledge. That is, it wasn't clear how the alternatives pulled out preference. Group A went for one interpretation... and got dramatically different results than the other groups, it looks like. We would have been helped by better question framing."*—Fish biologist
>
> *"Please provide more clarity about what each decision choice is in support of. Our group had more than one way of interpreting what some of the questions were asking."*—Natural resource conservation scientist

Participants sought more clarity and were challenged by the idea that the AHP model did not distinguish between their preference judgments and their expert opinion based on "best available knowledge". Our AHP, based on pure preference information, allowed DM understanding of the problem to drive prioritization, regardless of the actual information the DM had about the problem [183]. We designed the AHP to focus on key issues important to DMs. It would necessarily produce different results from group to group or user to user (as with any MCDA). However, participants balked at the open-ended framing of the pairwise comparison activity and, consistent with academic epistemologies, were troubled that there was no additional information from which to learn. Participants sought clarity about decision alternatives and criteria, and questioned the purpose that they all served in preference elicitation if the descriptions were not clear or precise. Again, it is important to remember (for context) that our participants were all researchers or academics, and in DDST 1 the decision alternatives and criteria included very little descriptive information. Consistent with academic training, participants were uncomfortable making general judgments without additional information support.

Post-survey feedback and researcher observations suggest that lack of specific information ("scientific data") was another key issue contributing to participant discomfort in preference judgments:

> *"We felt we needed more information to decide between [decision alternatives] - is this an opportunity to include scientific data?"*—Fish biologist
>
> **Excerpt from researcher notes on 6/4/18:** "The magnitude of the situation matters when it comes time to make a decision" (Example given- Storage, for drinking water. Is it for a city of 100,000 people or for 5 families?)

Indeed, there was little supporting information for participants, other than the information provided in the Dam Decision Scenario document and PPF handout (Appendix K, section 1.4.), because our AHP was designed for pure preference elicitation and did not include actual criteria data for any decision alternative. Since no data were provided to participants, it follows that units of measurement were not included either. It seems that even just adding in units of measurement could have potentially addressed a lot of participant confusion over the magnitude of the decisions at hand while still not offering any specific data. Scientific data and explicit description of units was something that the research team incorporated thoroughly into DDST 2 and DDST 3 based on participant feedback and the obvious discomfort our team observed while participants attempted to work through the 'pure preference' elicitation activity.

Study 1 was the first time that participants used the tool from beginning to end, including graphed results from the AHP (Figure 40) and mapped results from the MOGA-MCDA (Figure 41). During the individual results discussion and mapping of MOGA-MCDA outcomes, we identified a DDST calculation error, where the AHP was erroneously handling preferences and the MOGA-MCDA was recommending the reverse decision alternative of what it should have been (i.e., if a participant was prioritizing fish passage in their decisions, they were receiving recommendations to install additional hydropower capacity or upgrade turbines). The calculation issue (missed in multiple rounds of testing with invented preference data, section 5.2.2.1.) confused participants at the time of the workshop and added to the overall sense from participants that the model was a black box, and generally not understandable. Because the MOGA was dependent on MCDA preference values, the MOGA-MCDA results also generated an incorrect result. Participant feelings about MCDA as a black box extended to their confusion about MOGA-MCDA results.

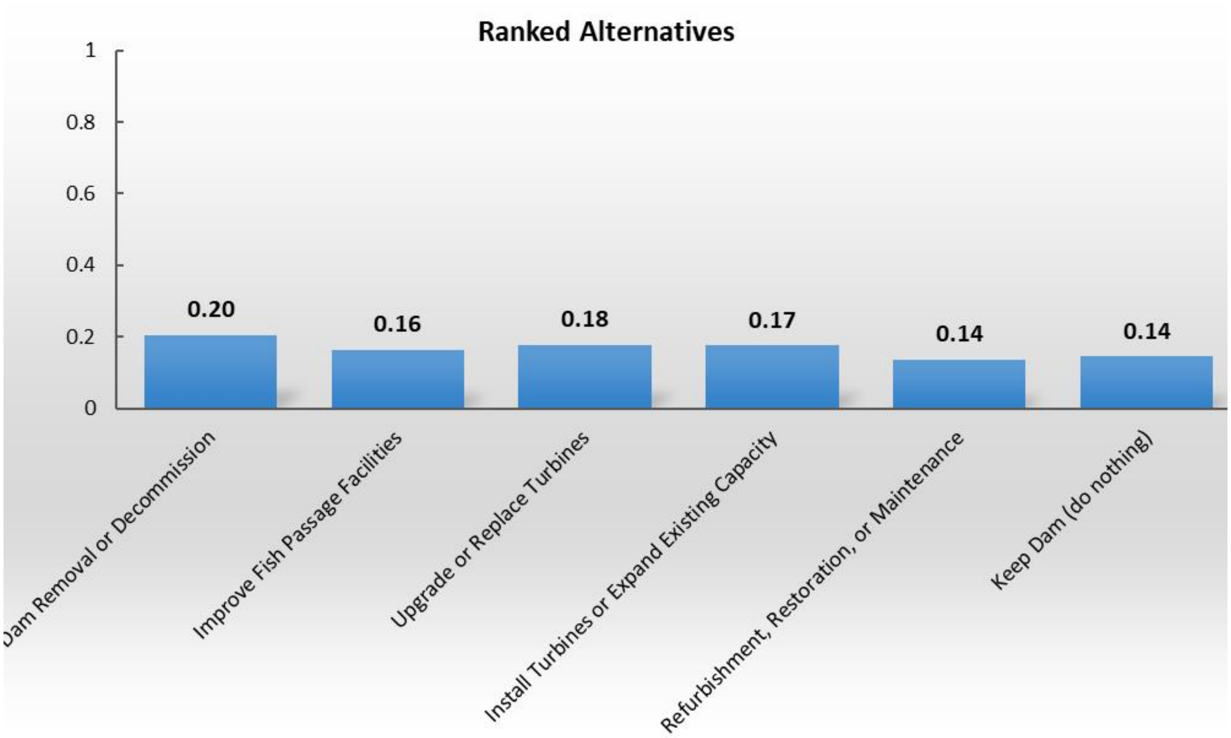


Figure 40. AHP results from study 1, an example of pure preference output (no criteria data) from one of the groups. Due to the reverse-calculation problem, decision alternatives with the lowest rating were considered 'best' in the context of the AHP output.

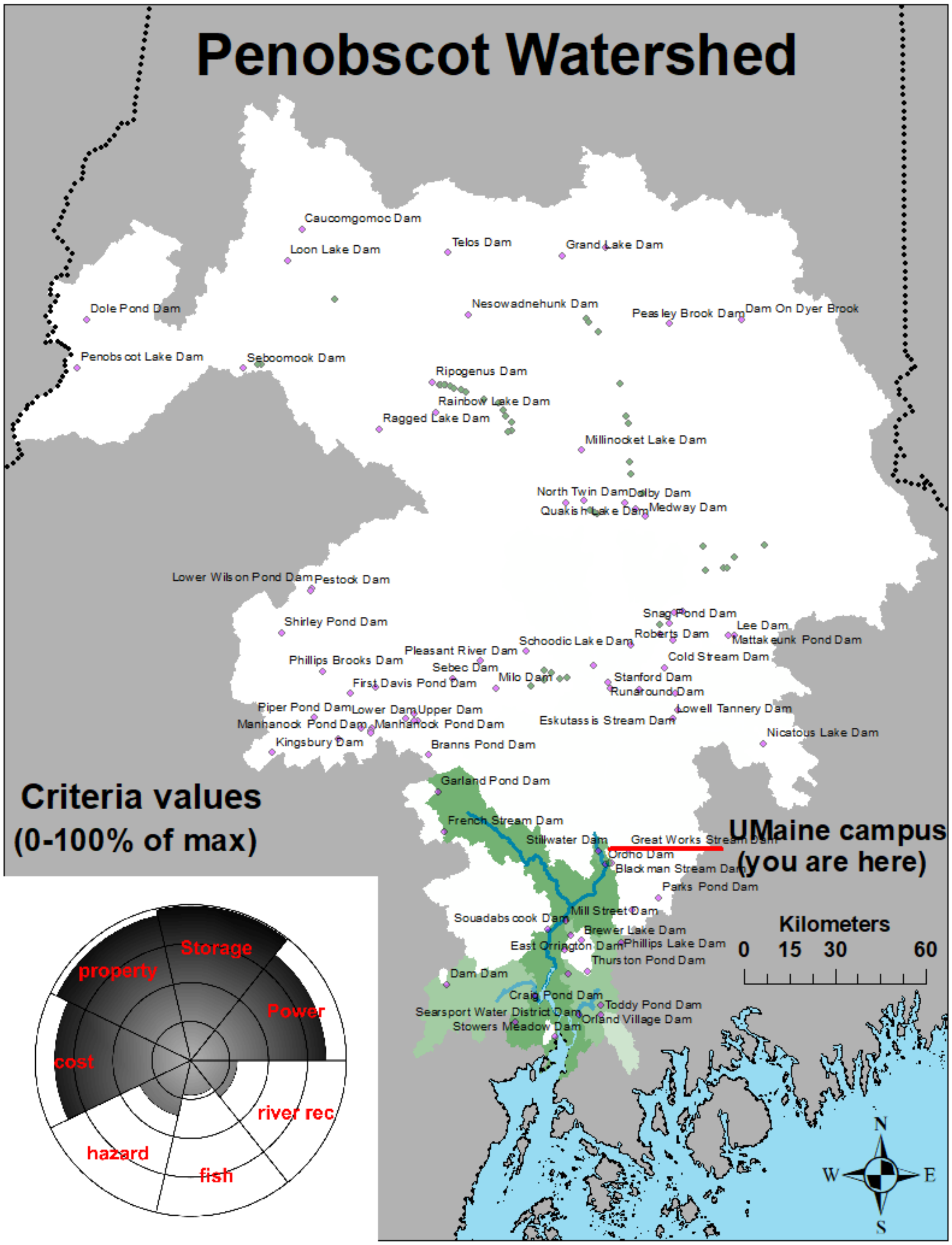


Figure 41. DDST 1 MOGA-MCDA mapped output with a rose plot. Red underline represents a dam removal site.

Approximately half (n = 10) of our Study 1 participants (total N = 18) responded to the post-survey. Overall, participants reported at least somewhat liking the watershed maps (~90%), PPF diagrams (~70%), discussion/debrief (~90%), overall experience, (~70%), results presentation (~70%), facilitation style

(~70%), and preparation material (i.e., participant packet, ~70%) when asked: “How much did you LIKE or DISLIKE the following workshop materials/activities?” (Figure 42). Most study 1 participants felt neutral about or disliked group negotiation (~50%), the watershed-scale scope (~50%), and the instruction about AHP MCDA in the beginning of the workshop (~50%). Based on participant comments from the post-survey and researcher observation notes, it seems that the watershed-scale decision-making contributed to participant dissatisfaction with other workshop activities. Participants shared survey feedback about the scope of the decision scenario:

> *“While this tool seemed to tackle the Penobscot watershed as a whole, it seems that it would be more effective as a decision support tool at a smaller scale.”* –Wildlife conservation scientist
>
> **Excerpts from researcher notes on 6/4/18:** “If you were talking about a specific dam, all of this would be much clearer.” [researcher name or field not recorded in observation notes] “If we were looking at a lot of dams and we knew them well then this would be better.” [researcher name or field not recorded in observation notes]

This comment was representative of the overall critique of generality—participants were not comfortable assigning importance scores to decision criteria at such a broad scale, *especially* where they were presented with no data to inform such a decision. The watershed-scale was generally perceived as impractical for decision making. We made efforts to address this feedback in the student workshop in 2019, scaling back from the Penobscot watershed scale to focus on a few key dams in the watershed coming up for relicensing in the next decade. The DDST received the greatest number of “dislike” responses (60% somewhat disliked or disliked a lot), which was related to the AHP methodology. Participants were fatigued by the series of pairwise comparisons, and the watershed-scale decision scenario only exacerbated the issue. Participants had to make more than 100 judgments while using the tool, and a watershed-scale decision scenario made those judgments more challenging (which seems to have been related to the lack of unit of measurement information and data), on top of the AHP calculation error, which returned results opposite of what was expected based on preference information. Based on our experience, participant fatigue was problematic and seems to be an issue downplayed in the academic literature where researchers opt for AHP. In the studies where researchers do mention the potential for participant fatigue, they continue to use AHP as an MCDA methodology in their other studies. Thus, it was our perception that the issue was not prohibitive to the use of the tool; however, after experiencing it with participants, and seeing the general dislike of the DDST, we would caution against others using it in a participatory context at all, unless dealing with a very small number of decision alternatives and criteria (3 each).

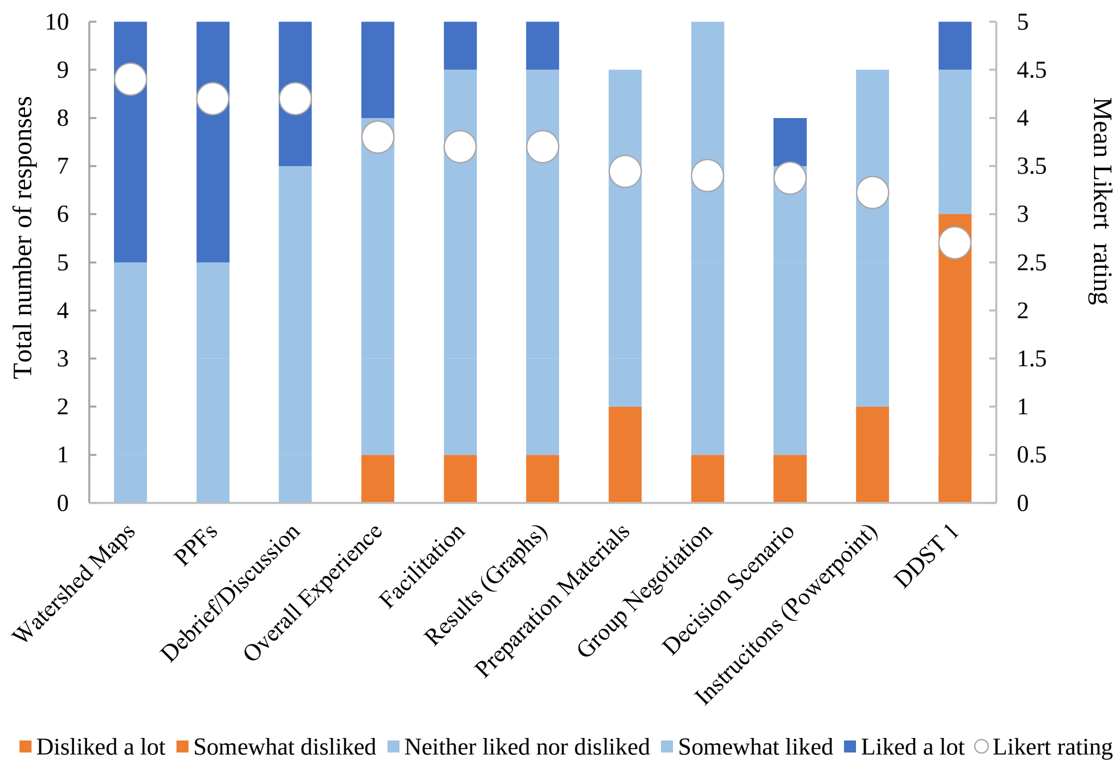


Figure 42. Study 1: Post-survey participant responses to the question: How much did you LIKE or DISLIKE the workshop materials/activities? (n=10). Circle indicates average Likert rating.

When asked how much they LEARNED from the workshop materials/activity, most (70% - 100%) Study 1 participants learned from some or all aspects of the workshop (Figure 43, original 1 – 3 Likert scale results were rescaled to a 1 – 5 Likert scale for ease of comparison with Figure 42 and survey results from Studies 2 and 3). Even though most participants reported disliking the DDST, most participants reported learning at least a little bit from the DDST 1. The same is true for other materials or activities. Even if they did not like an activity, participants reported that they learned something, e.g., participants reported mixed feelings about 'liking' the group negotiation activity, but 100 percent of participants reported learning a little bit (or more) from the negotiation. The same is true for the overall experience. Participants reported in a mixed way about 'liking' the overall workshop experience but ultimately learned from it (100%).

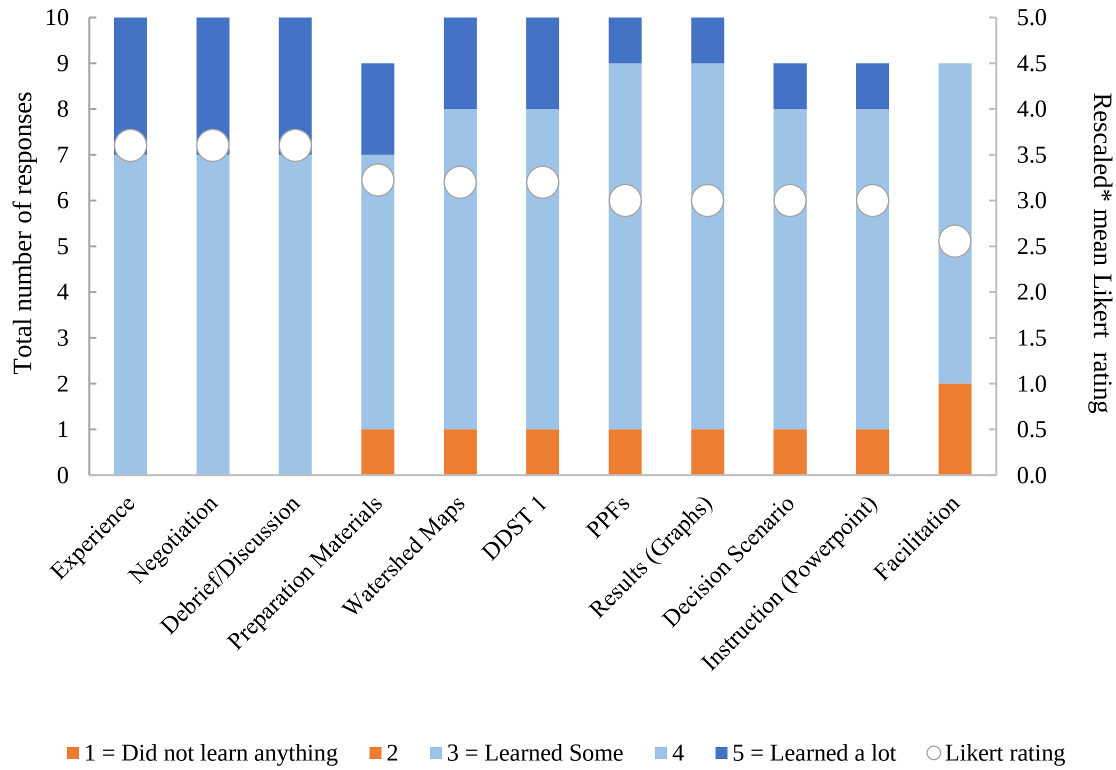


Figure 43. Post-survey participant responses to the question: how much did you LEARN from the workshop materials/activities? (n=10). * = rescaled from original 1 – 3 scale to a 1 – 5 Likert scale for ease of interpretation.

Overall, participant feedback indicated that the DDST was not stakeholder ready. It was clear to the research team that we needed to frame the decision differently for enhanced participant buy-in. Likewise, participants commented that specific language in preference elicitation was necessary:

Excerpt from researcher notes on 6/4/18: *"Maybe you should word the question as 'preference' rather than 'importance.'"* [researcher's field not recorded]

The question phrasing in the DDST for each pairwise comparison, “In your opinion, how much more important is (b) than (a)?” was perceived as problematic, adding to the confusion in the preference elicitation activity. I used this phrasing (instead of “how much do you prefer (b) over (a)?”) in DDST 1 because my goal was to get participants to approach the activity as a prioritization, directly engaging in tradeoffs rather than using preferences to signify tradeoffs. “Important” was a word that I maintained in DDST 1 – 3 because it forces the idea of tradeoffs in the preference elicitation activity and emphasizes the idea of prioritization: simply put, not everything can be important.

Although the quantitative survey responses helped gauge the general participant sentiments about the workshop, the open-ended questions asked for feedback about how to improve our model and workshop design. A participant who was familiar with MCDA shared the following in post-survey comments:

> *“[Give] fewer options for the scale of preference, clearer instructions on how our preferences would be reflected in the results…shorter number of questions, combine turbine options to a single option. I would also avoid talk of a reciprocal scale if possible. I think you could have details on the MCDA methods you're using available if stakeholders are interested, but I wouldn't go into that level of detail before they use the tool. Might just be confusing and a little intimidating.”*—Civil/environmental engineer

The same participant who was more familiar with MCDA expressed doubt about AHP as a successful approach for a participatory setting because of the burden placed on decision makers to consider pair after pair of decision alternatives using an unfamiliar scale (Saaty’s Fundamental Nine-Point Scale). He suggested outranking approaches as a potential alternative to AHP, with comparative testing between the two types of MCDA:

> *“I wonder if there is a way to test outranking approach [sic] vs. an AHP approach (or if that would even be useful). Maybe you can get together a focus group for the next iteration?”*—Civil/environmental engineer

These methodological critiques prompted reflection about our research priorities (i.e., participatory considerations vs. theoretical modeling considerations), and what was most important to our research design. We also considered observed challenges with AHP as fatiguing to participants. Was it more important to create a user-friendly experience for participants, or to ensure that the model elicited preferences thoroughly? What were we gaining from the AHP that we could not gain from another, less fatiguing, form of MCDA? Our research team decided that a tradeoff between participation and modeling would be necessary if we wanted to design a participatory DDST to be shelf-ready, without the need for a researcher to mediate between the DM and the model. The end goal for the DDST was to design something that would be user-friendly and useful, and it seemed based on our observations that AHP was neither of those things. I returned to the literature and reassessed the selection of AHP for group participatory MCDA (which resulted in Ch. 4). Ultimately, this reflection process and review of the literature with a fresh outlook contributed to the decision to shift away from AHP and use only WS MCDA with direct (slider bar) preference elicitation in DDST 2.

Finally, group negotiation was a challenge. No participants commented about group negotiations in their post-survey feedback (except to mention that they were unable to complete the activity due to time constraints), but majority voting was the negotiation strategy adopted by the groups who completed the activity. Groups who did not select voting did not finish the group negotiation, suggesting that they could have benefited from the support of a facilitator or some additional instruction/structure for group preference elicitation. Based on researcher observations of the difficulty experienced by groups who elected to compromise or achieve consensus on their preference judgments rather than vote, our research team opted to incorporate an additional group decision mode (with explicit instructions) into the DDST 2. The research team was still interested in seeing how groups organically determined strategy for negotiation, so we did not include a formal facilitator role in our planning for Study 2, other than to allow the groups to self-select a participant to fulfill that role, with general guidelines about what the role meant.

Study 1 participants were critical of the key workshop components (Figure 44): model accessibility (e.g., 70% did not think it was accessible), manageability of the group negotiation (e.g.,60% did not think it was manageable), and the role of the workshop in enhancing user capacity for dam decision participation (e.g., 60% did not agree that the workshop enhanced their decision-making capacity, 50% did not think they would use a similar process in their own decision making). Reflecting on the state of the DDST at the time of Study 1, this critical assessment makes sense. Most (90%) researcher participants responded neutrally to questions about workshop 1 outcomes sustainability, likely because sustainability was not defined, but perhaps also because most groups did not finish the group negotiation due to time constraints. Likewise, 90 percent of participants disagreed that the outcome was equitable because there was no outcome. I was surprised to find that 40 percent of researcher participants seemed to think that consensus was achieved, when most groups used majority rule as the strategy for 'negotiating' about shared preference ratings. On the positive side, and as we saw in participants' responses to whether they LIKED or DISLIKED workshop materials/activities, group negotiation seemed to be a useful experience (70% thought the group negotiation was personally useful to them). This result is interesting considering the mixed response to "the group negotiation was manageable." Likewise, "the group negotiation was successful" had a mixed response, with half of participants agreeing, and the other half neutral or in disagreement with the statement. Workshop 1 facilitation was generally considered (60% "agree") adaptive, but researchers observed considerable frustration amongst participants about the guidance they received when asking about how to think about the decision criteria or alternatives while rating them. These results indicated to our team that our time would be well spent in a) refining the DDST to enhance accessibility and b) building in some group negotiation support (the Microsoft Excel spreadsheet in Study 2 was the prototype of this).

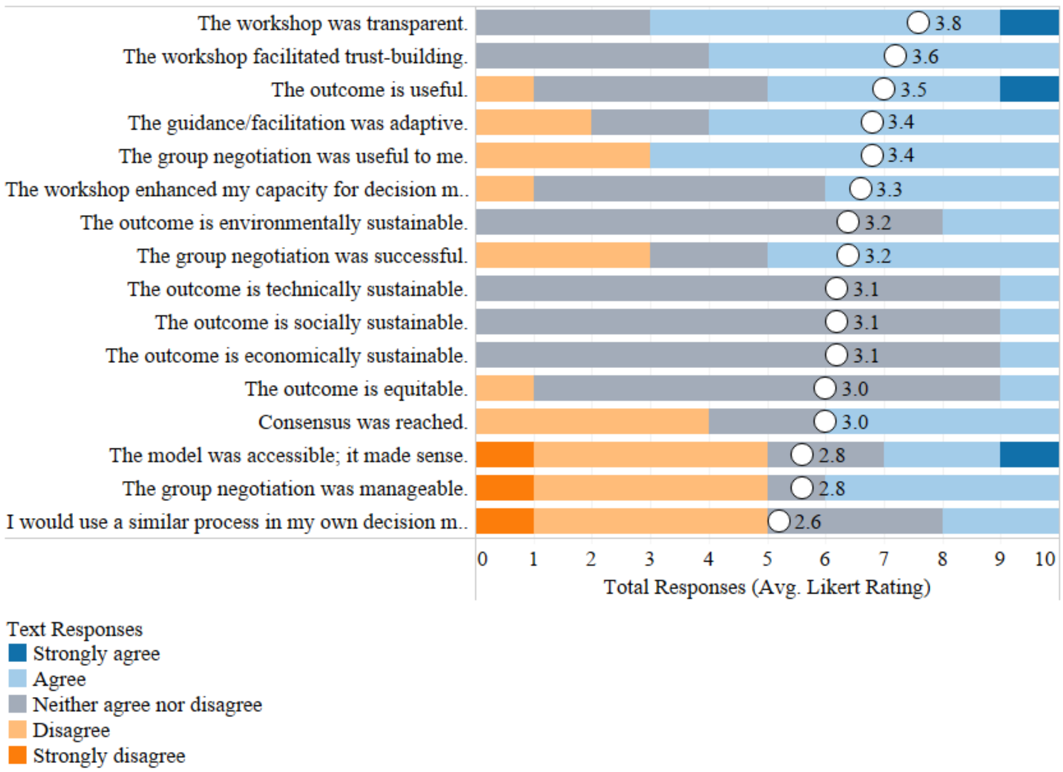


Figure 44. Researcher post-survey responses evaluating workshop components, including outcomes, Study 1 (n=10).

Study 1 provided several important lessons in participatory model development and highlighted key opportunities for improvement. First, the calculation error inspired rigorous testing by all DDST researchers (to simulate different users) and the use of multiple simulated/stylized preference datasets (e.g., equal preference, homeowner preference, fish-only preference) to further validate the model and ensure that future DDSTs did not result in confusion for users. Second, Study 1 helped us to better understand the needs of participants for clear guidance in the UI and anticipate potential user experience (UX) issues relating to both preference elicitation strategies and problem scoping. Study 1 participants found the pairwise preference elicitation process fatiguing, and a participant familiar with MCDA methods actually suggested abandoning AHP altogether in favor of another, less demanding approach. Participants also expressed a need for additional scientific data. Where the AHP-based preference elicitation was based on pure preferences, participants felt hindered by the lack of information supporting them in their decision making. Third, Study 1 revealed a necessity for additional structure in the participatory process. Where the research team had decided to leave the negotiation open-ended, most participant groups selected the most efficient strategy (voting) in order to complete the 'assignment' and groups opting for consensus-based strategies became mired in debates over the 'right' way to think about decision criteria (see researcher observation notes excerpt from 6/4/18 about over-extrapolation). This observation prompted the use of Excel spreadsheets for averaging group data as a starting place for negotiation of shared preferences in Study 2, to streamline the group negotiation by providing a starting point for discussion. Ultimately, testing the initial AHP-based and watershed-scale DDST 1 with researcher participants guided UI/UX development decisions for later DDSTs and prompted my decision to start from scratch with a new MCDA model and software program for DDST 2.

5.3.2. Study 2 Outcomes

Recall that for the analysis of Study 2, I have two additional forms of data to pull from for results interpretation: a) group summaries (from the workshop), and b) individual participant notes on DDST 2 (from the homework prior to the workshop, where participants were asked to use the DDST 2 individually and reflect on their experience). Individual participant notes on the DDST 2 answered a series of questions about UI/UX:

1) Are the instructions clear?
2) Do the decision criteria make sense?
3) Is the tool user-friendly?
4) Do you understand the results? Why or why not?
5) What specific suggestions do you have to improve the project?

Participants generally took a student-level approach to problem-solving, which was to make the best use of the information they had and finish the activity as efficiently as possible. Study 2 participants felt that criteria were not understandable in the context of specific decision alternative preferences, that preference elicitation was unclear and not user-friendly, and that they needed more data. Participants wrote in their

DDST 2 homework notes that they were unsure as to why their decision criteria scores would change at all when considering different alternatives:

> *"For the most part, the criterion for dam decisions could be ranked relatively the same and the tool could be used for a hypothetical dam or specific ones as we were doing."*
> -Student
>
> *"Explain the criteria for decision making a bit more perhaps. Why should I change how important I think [a decision criterion] is based on whether we are discussing fixing the fish passage or improving the capacity of the generators."* -Student
>
> *"The online tool had too many options to choose from, I don't think my answers changed much between [decision alternative] lenses when looking at the criteria."* -Student

Understanding of criteria and preference elicitation clarity seemed entangled, from the participants' perspectives. The fact that we were asking for decision alternative-criterion specific preferences confused some participants, leaving them wondering about why they might need to think differently about criterion values for specific decision alternatives. Many participants felt unsure if they were doing the activity 'right'. Participant post-survey feedback provided some additional food for thought:

> *"It was difficult to understand how we were supposed to rank the importance of each factor. Were we supposed to choose what* should *be considered for each alternative, or what we thought was most important in general?... For example, removing or maintaining a dam without fish passage facilities would have vastly different effects on fish populations, but maintaining those populations is equally important, regardless of what decision is made."* -Student

The idea that what "*should* be considered" and "what we thought was most important" were equivalent seems to have stumped some participants. These comments led our research team to reconsider the preference elicitation strategy for DDST 3 to better streamline the user experience. We had designed the preference elicitation to be criterion-alternative specific, but WS does not require this thorough approach and it seemed to confuse participants. We took this critique seriously for DDST 3 and performed a complete re-organization of the UI to minimize confusion from participants and streamline preference elicitation to be criterion-specific only. Criteria preference questions came across in group work, too. When participants needed to work together to come up with a shared set of preferences, many groups found that they did not feel comfortable rating qualitative criteria at sites near communities not their own. I pulled this illustrative quotation from the group summaries:

> *"We found it difficult to value aesthetics, industrial historical importance and town identity in communities that we are not a part of and have little knowledge of. Including more information about the towns in the dam fact sheets would be helpful in making these decisions."* -Student

The patterns in the group feedback are clear: for the most part, student participants felt they were not familiar enough with the subject matter to make decisions, or they did not have enough data upon which to conclude, even with the support materials given. Specifically, participants expressed a desire for additional information, particularly on the 'social' decision criteria: aesthetics, industrial historical value, town/city identity, and indigenous cultural heritage (Table 27). Context for site-specific decision making was important to student participants. This need for additional data reflected the feedback from researcher participants in Study 1 and makes a lot of sense coming from participants in a similarly academic setting.

In general, it seems that individual participant DDST 2 notes and group summary patterns aligned (Tables 31 and 32). Individuals and groups both felt that the decision criteria were confusing, the purpose of the activity was confusing or unclear (in the group activity I interpret the expression of 'challenges' in valuation and the need for a facilitator or additional instruction as some of that confusion). User-friendliness and criteria ratings were issues that were closely tied together. Students expressed that a different slider scale could have cleared up confusion about the criteria rating, but more information was also needed for decision context. While the written instructions explained both the decision alternative context and how to use the slider scale (and in many cases, there was evidence that students simply did not read the instructions, as half of the groups did not seem to realize there were Dam Data Tables to reference until well into the group negotiation process), it was also clear from student comments that improvements could be made to the UI to make the user experience more intuitive. This feedback encouraged our research team to design the DDST 3 with participant packet materials integrated into the tool using web links and data tables.

Table 31. Interpretive summary of comments from student feedback.

Category	Themes in Individual Feedback	No. Responses
Instructions	Task is clear	7
	Task is unclear	11
	Written instructions are too long	7
	Purpose confusing	7
Criteria Rating	Rating slider is good	3
	Rating slider is bad	4
	Suggestions for slider improvements (e.g. 0 – 100)	5
	Criteria are confusing	7
Results	Interpretation is good	9
	Interpretation is bad/not helpful	1
	Graphs are good	9
Overall	User-friendly	15
	NOT user-friendly	4
	The valuation process is unclear	15
	The process takes too long	1
	The website crashed or malfunctioned	5

Table 32. Interpretive summary of comments from student group notes on the workshop.

Category	Themes in Group Feedback	No. Groups
Instructions	Need additional instruction	1
Ratings	Suggestions for slider improvements	3
	Need more information about criteria	3
	Criteria are confusing or unclear	3
Discussion	Could use the support of a professional facilitator	4
	The valuation process is challenging	5
Overall	Google Sheet for data entry could be improved	3
	Facilitation required too much tech and data entry	2

Despite participant confusion about the preference elicitation activity, participants seemed to have no trouble understanding or interpreting their graphed responses (recall: graphed responses were based solely on the preference elicitation activity, and not reflective of the MCDA ranked output). One participant reported the following about the graphed preference results:

"I enjoyed seeing my results in the bar graph. I think it was the most useful aspect of this project." -Student

The graphs seem to have helped in results interpretation, despite whatever confusion there may have been in preference elicitation. Other students wrote in their DDST 2 individual notes:

"I do think I understand my results, the graphs at the end making understanding the data much easier. I don't know if I could have grasped or been able to compare my results without the graph." -Student

"I understand the results. It's just summing all the criteria that you chose. The criteria with the most points should be the one you focus on or is the most important to you." -Student

It seems that the bar graphs themselves were a useful and understandable outcome for participants because they were able to visualize what their preferences looked like relative to one another (Figure 45-47). Bar graphs for DDST 2 described the breakdown of participant preferences across criteria and decision alternatives. While Study 2 participant criteria scores varied somewhat across individuals and (to some extent) dams (Appendix M reports MCDA outcomes), most individuals varied their scores only slightly between dams and decision alternatives. In the graphs shown here, I used group average preference information across all 3 dams: West Enfield, Medway, and Ripogenus.

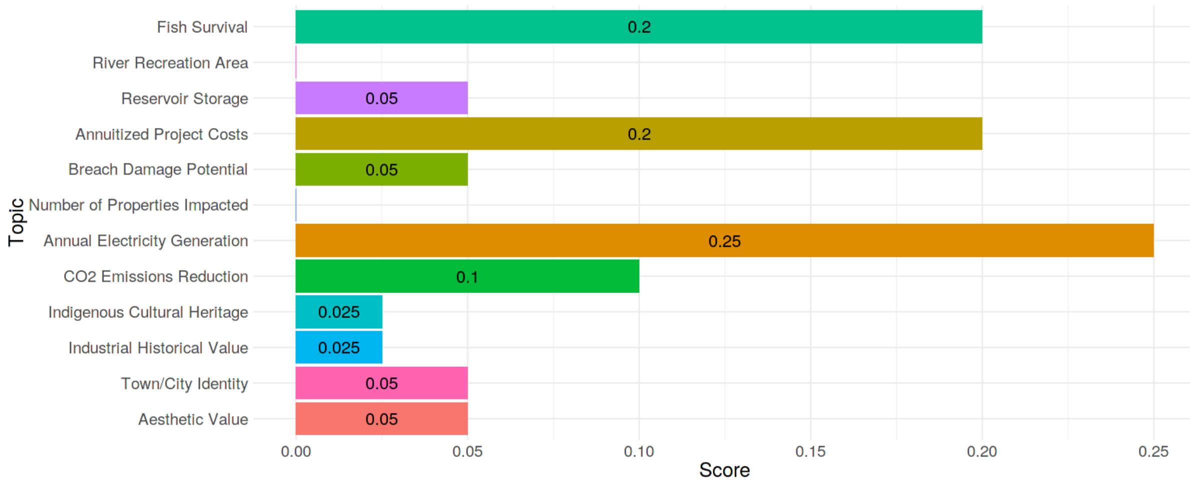


Figure 45. Study 2: Average (3-dam) participant criteria ('topic') preference scores specific to Improve Hydropower Generation decision alternative for student Group 1. Example of decision alternative-specific results; recall, scores must sum to 1.

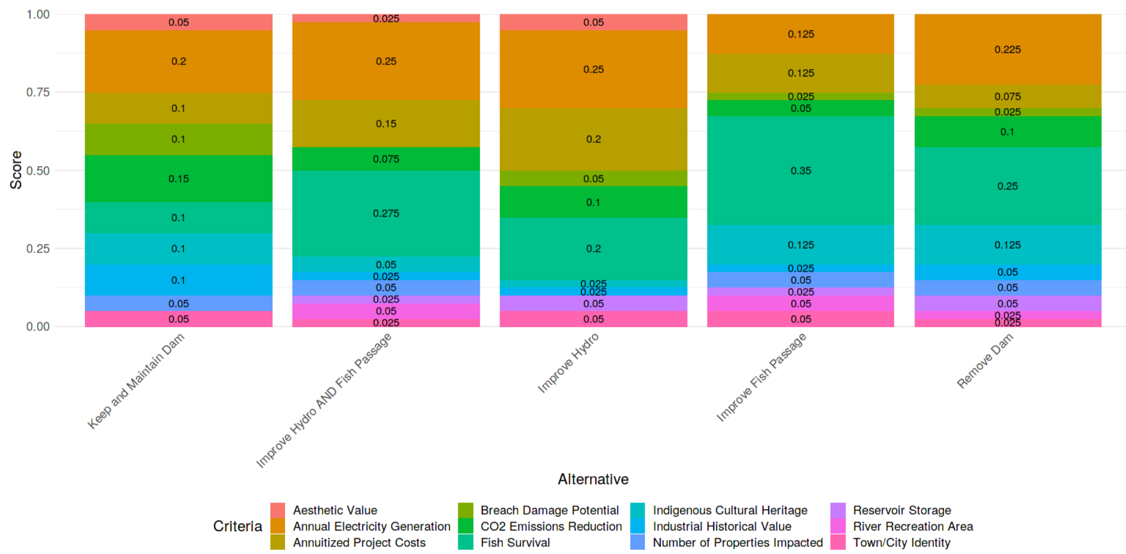


Figure 46. Study 2: Three-dam average criteria preference scores relative to their decision alternatives; student Group 1 output.

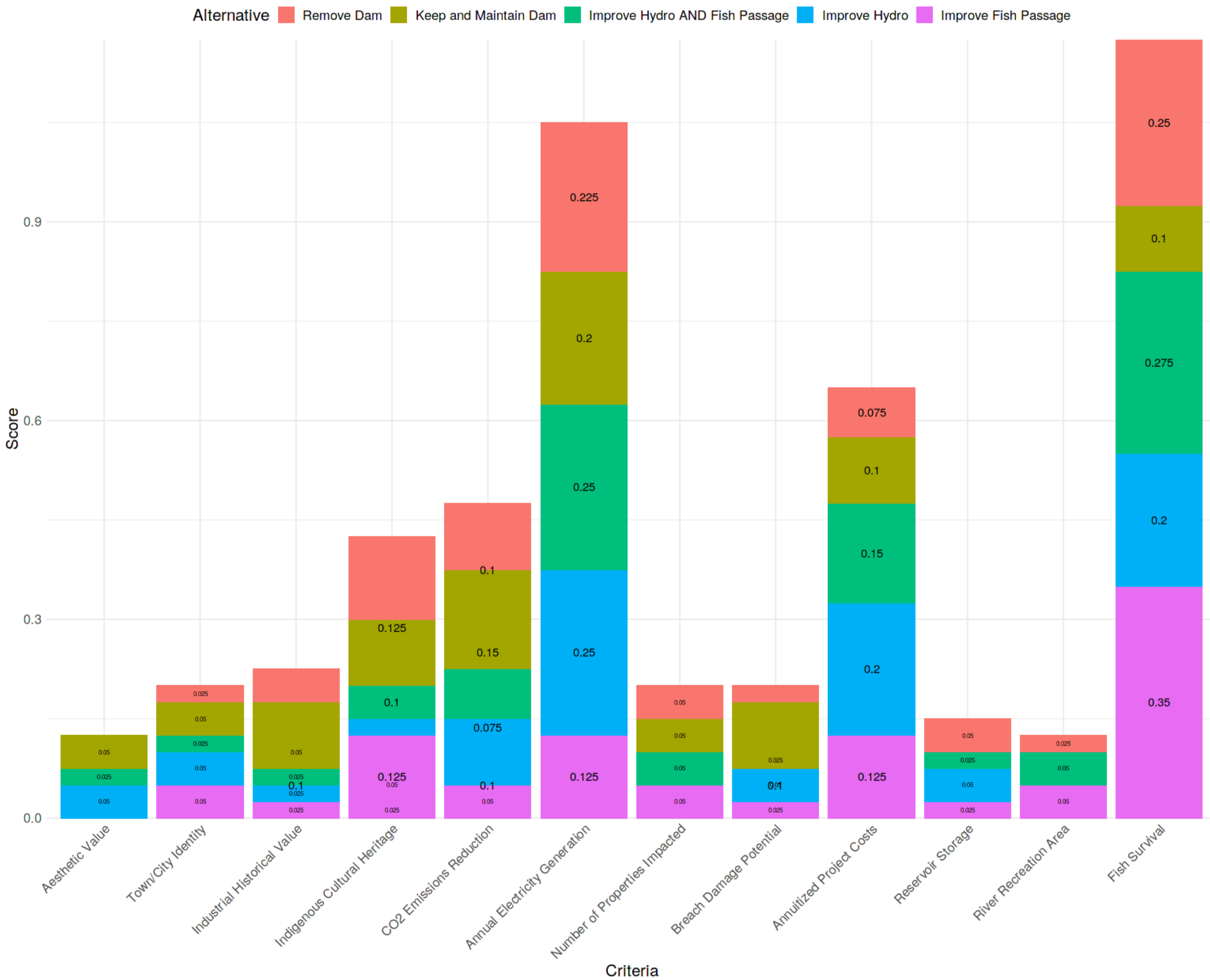


Figure 47. Study 2: Average (3-dam) group criteria preference scores are broken down by alternative, to demonstrate priority differently; student Group 1 output.

It is important to note that while the bar graphs of user preferences were clear, participants did not understand the MOGA-MCDA output. In DDST 2, we kept the WS aggregation and ranking in the MOGA-MCDA portion of the tool separate from the UI portion of the tool, so the WS calculation was again hidden from participant view. And, like the researcher participants from Study 1, student participants never actually saw the final MOGA-MCDA ranked output in graphical form. Similarly, because the MOGA-MCDA model was not something participants could examine, they had no way of back-tracking to understand their results. The DDST 2 MOGA-MCDA was perceived as not understandable, or as a ‘black box’, much the same as in DDST 1. The lack of transparency was a major critique that students had about the DDST 2 that did not come across in group summaries or post-survey feedback, but was very much apparent in the workshop debrief and noted in researcher observation notes. Looking at Figure 48, one can see how Group 1 students could have been confused, because the MOGA-MCDA incorporated their average preferences across all sites, and resulted in the removal of two dams despite their preference for annual electricity generation (consistent across all decision alternatives). Even knowing that data were driving the MOGA-MCDA results in addition to the user preference information, students did not have access to those site-specific discrete data (see Appendix K for the Dam Data Tables participants had access to) and felt hindered in their sense-making about the mapped results. The rose plot in Figure 48 was particularly problematic for students because they did not see their averaged preference values reflected there (because the rose plot shows the weighted normalized criteria values). Access to site-specific Dam Data Tables was something we improved in DDST 3, and we brought the calculation steps of the MCDA front and center in the UI in site-specific result tables (more in section 5.3.3.) to better facilitate participant interpretation of results. The mapped MOGA-MCDA output was something we excluded from DDST 3 in our effort to make results understandable and believable for the stakeholder workshop, since we ran out of time in troubleshooting while attempting to integrate the results into the web app (section 5.2.4.).

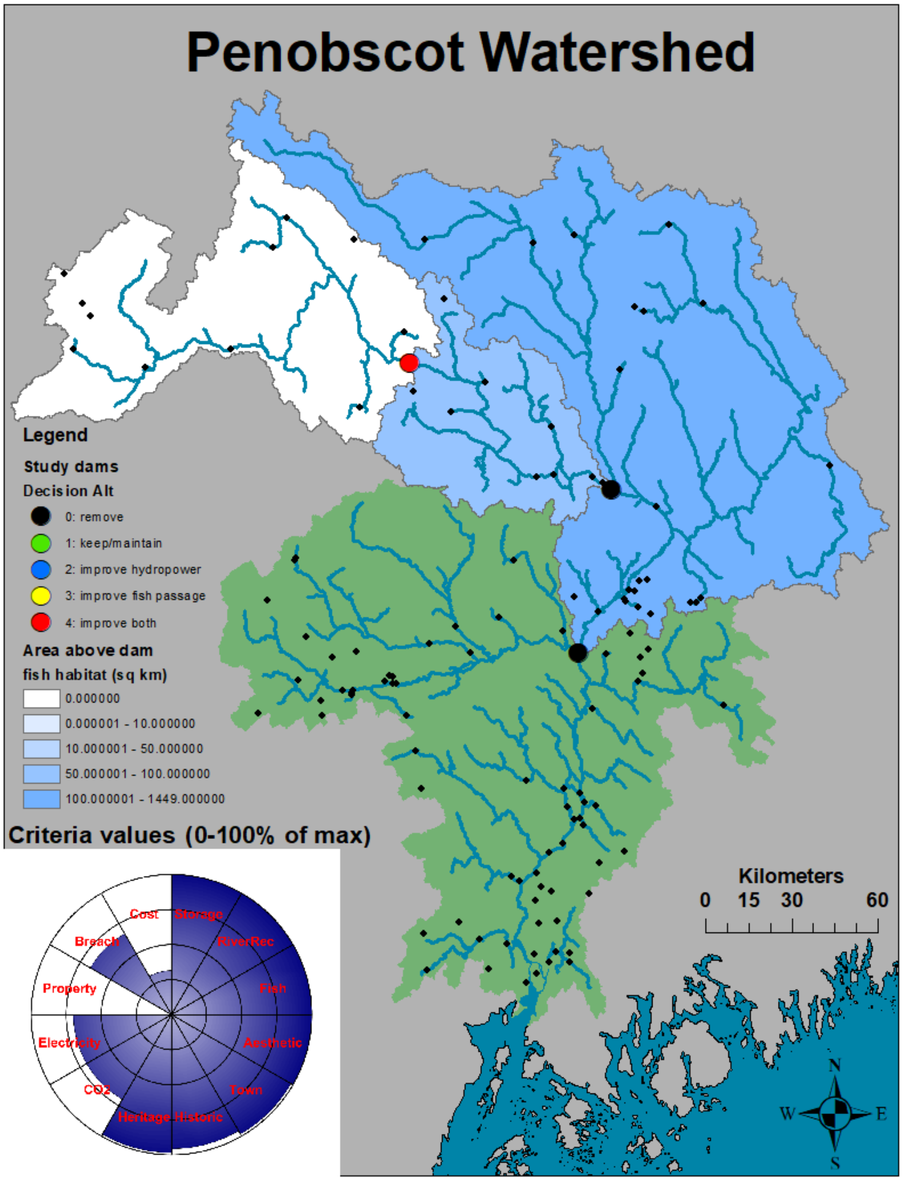


Figure 48. MOGA-MCDA mapped output example corresponding to group 1 average preferences across all dams.

By contrast, the group negotiation activity was seen in a positive light by student participants. Students shared the following perspectives about group negotiation in their post-surveys:

> *"I liked talking with people about the decision alternatives to see if people prefer with me or not."* -Student

"Being able to think on my own and then hear the group's thoughts allowed for a reflection on your values and the shared values. It was adding another perspective which is always good." -Student

Learning from one another through discussion (normative learning) seems to have been an important outcome of the student workshop in Study 2. Participant post-survey feedback also highlighted learning about the 'bigger picture' from their classmates during the group negotiation activity:

"Group discussion fostered additional analysis an individual might have otherwise overlooked." -Student

"I learned that we really need to look at the whole picture, and see if the results make sense given the pattern of dam locations and whether certain improvements would be feasible for a given dam." -Student

This result is intriguing, particularly because the final negotiation strategy that most groups used to achieve agreement was voting, rather than compromise or consensus. While participant groups relied on discussion as a way to understand more about the decision context and draw from each other to better understand the decision problem, they seem to have been satisfied with majority vote as a means of accomplishing the task at hand. The groups not employing majority vote as a strategy did not complete the assignment, so it seems that students using majority vote were either a) simply interested in completing the assigned task or b) they already agreed with one another. Groups did not do a thorough job of reporting their selected strategy for decision making, so it is impossible to tell with accuracy how divided the voting was in each group.

A little over half (57%, n = 20) of our participants (total N = 35) filled out the post-survey. As in Study 1, participants responded to post-survey questions about how much they LIKED or DISLIKED workshop materials/activities (Figure 49). In general, participants liked the group negotiation activity (80%) and DDST results graphs (70%), but fewer liked the discussion/debrief (55%) and the multi-dam scenario maps (MOGA-MCDA result, 45%). Student participants were, on average, more ambivalent about the introductory Powerpoint presentation, overall workshop facilitation, overall experience, and the DDST 2. On average, students reported disliking the Dam Factsheets, results presentation, activity instructions, and rose plots. These were the activity/materials that students mentioned needing additional information about (e.g., students wanted more information than the Dam Factsheets provided) or had the most questions about (e.g., rose plots, because they were not seeing their averaged preference information for the set of 3 dams), so the predominant 'dislike' result was not surprising.

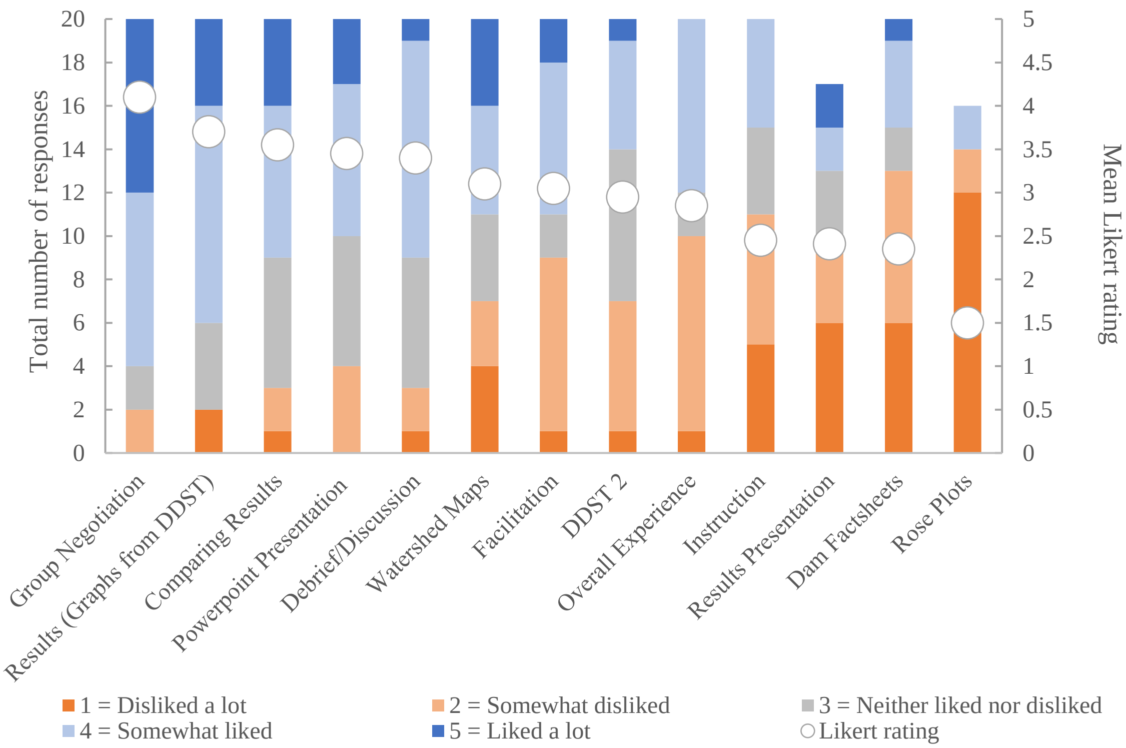


Figure 49. Study 2 participant responses to the question: how much did you LIKE or DISLIKE the workshop materials/activities? (n=20)

Participants also reported learning from the group negotiation activity (~95% "learned something" or "learned a lot"), DDST results graphs (~79%), discussion/debrief (~90%), and the multi-dam scenario maps (MOGA-MCDA result, ~74%) (Figure 50). By contrast, a considerable number of negative ratings were given to the following (indicating that more participants reported that they "did not learn anything"): DDST 2 (~63% "learned something" or "learned a lot"), Dam Factsheets (~63%), instructions (~61%), and results presentation (~53%). The rose plots (MOGA-MCDA result) rated extremely poorly (~22% "learned something" or "learned a lot"). Interestingly, participants did admit learning from many of the other materials and activities for which they reported dislike, especially from the overall workshop experience (~90% "learned something" or "learned a lot").

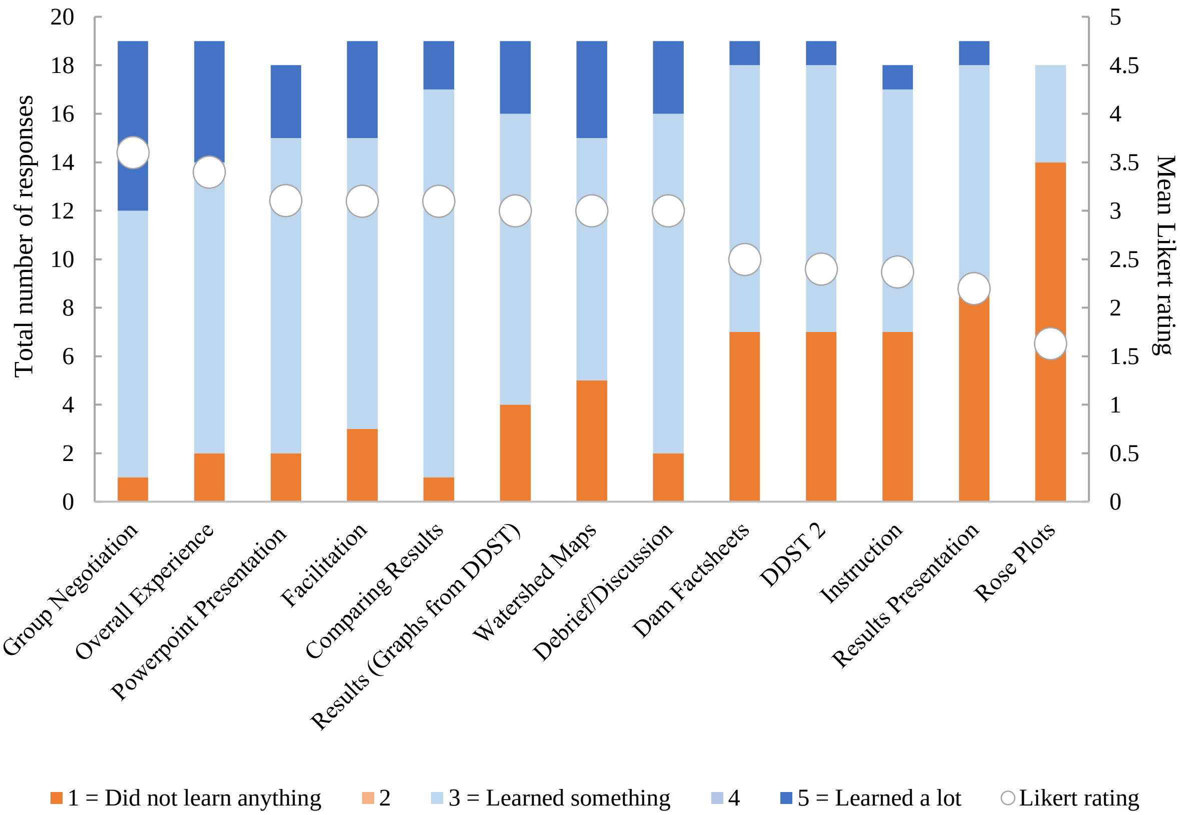


Figure 50. Study 2: Participant responses to the question: how much did you LEARN from the workshop materials/activities? (n=20)

All six student groups in the Study 2 negotiation activity were able to complete the negotiation activity for Medway, but not all groups had time to complete deliberations over shared preferences (even those using a voting strategy) for West Enfield and Ripogenus dams during the workshop. Evaluation questions on the post-survey provide some additional nuance to my understanding of participants' attitudes toward workshop materials and activities. Group negotiation received a favorable assessment. Participants agreed that the negotiation process laid the groundwork for trust-building (60%); gave equal access, standing, and balanced influence to all participants (60%); facilitated consensus-building and outlined structured standards for conflict resolution (~63%); was well-suited to the specific application and simulated a real decision-making process (60%); and provided opportunities for their clarifying questions, actively incorporated their input/feedback, and inspired trust (80%). Participants' open-ended survey responses reflected this as well:

> *"I was able to ask clarifying questions with my peers. The struggles and confusion I experienced individually were [something that others] related to - which made me feel better and more comfortable when going through the group negotiation process…"*
>
> -Student

DDST-related assessments received considerably more neutral and negative responses than topics relating to group negotiation.

Participants in Study 2 made the connection between the workshop and model refinement—students agreed (~77%) that they actively participated in model construction and their feedback was incorporated into model development and refinement at multiple stages. They felt connected to the model-building process and that the resulting model addressed their key management needs. While I am skeptical that the 'agree' and 'strongly agree' responses were replies to every part of this loaded assessment metric (the metric was later refined for the post-survey in Study 3), it is clear that participants understood the role of the workshop in the DDST development process. Participants were honest, critical, and insightful in their individual DDST 2 feedback, offering further suggestions for additional DDST development. Students shared:

> *"In order to make this easier to use, I would recommend establishing some sort of scenario and background information that way it places the reader into a specific role where they then need to rank all of the criteria based on that situation."* -Student
>
> *"I don't like the 1/1 format, would be much more comfortable with 10/10."* -Student

Excerpt from my notes on 3/6/19: For instruction, students would have felt better supported with more examples… Having the decision matrix is key to transparency, so we do want to make sure to have an example that shows how the MCDA works in a step-by-step kind of way. We discussed using an example based on student inputs, so participants can see what would happen from slider bars to numerical preference output graphs, to hidden decision matrix and weighting, to the final mapped output. This would be good to provide a written example in some documentation of the model. Just an additional explanation of how WS MCDA works.

Student suggestions ranged from writing 'role play' scenarios to support preference elicitation (which I interpret as another call for more context-specific information) to adjusting the criterion preference scales and showing the MCDA steps. The 0 – 1 scale bothered people (even though the translation to 0 – 100 is just a matter of moving the decimal point over to the right), and it was an easy fix. Likewise, it was not difficult to include the MCDA tables in DDST 3 because based on student feedback about alternative-criterion preference elicitation being confusing (or redundant) and needing additional decision context, we knew we would need to reorganize the DDST around the dams instead of around the decision criteria (see navigation/menu tabs in Figure 34 and compare to navigation/menu tabs in Figure 30). Based on student comments, it seems that the biggest hurdle to model accessibility was the clarity of instruction and model intuitiveness. Study 2 participants also wrote the following in their individual DDST 2 notes:

"The instructions are clear enough that I was able to figure out what to do, but there's definitely room for improvement. I don't feel like it ever explained what I was doing other than how to work my way through all the tabs. Once in the alternative tabs it never explained what I was supposed to do other than make sure everything equaled 1. It explained that 0 was not at all important and 1 is extremely important? Was I supposed to be rating the importance in [sic] considering each option in regard to [sic] each

alternative? I never felt like I knew exactly what I was doing and that I was making it up the entire time." -Student

"Clean up the 'start here' page. Although the instructions were extensive- some were unnecessary, repetitive and confusing." -Student

It seems that DDST 2 missed the mark for user-friendliness. While many participants felt that the instructions were too extensive (refer to Table 31), some felt that more were necessary. Participants did not care for extensive written instructions or guesswork. Inadequate explanation came across not only in participants' open-ended reflections on the workshop in the post-survey but also in their notes taken while using the DDST individually.

Finally, groups also expressed a desire for facilitator support. One student group wrote in their summary of the negotiation:

"Provide informed non-biased facilitator to assist with questions and definitions with real stakeholder meetings." -Student

Excerpt from my notes on 3/6/19: In some cases, vocal students really drove the discussion. Group dynamics matter! Other groups didn't have clear leaders and facilitators seemed hesitant, so the discussion went more slowly. Group 1 was actually concerned about how the stakeholder discussion would go, and suggested that we use a professional facilitator for that workshop to help things move along.

Decimal values [on the slider scale] really seemed to throw students off. Having a 0 to 100 scale may address this in the model, but really what is needed is a facilitator to help participants understand better, answer questions in the moment, keep conversation moving, and reduce the "tech" burden felt by some groups.

My notes from the Study 2 workshop reflected this student-expressed need for a facilitator as well. Students were challenged by the request to facilitate amongst themselves, and some were able to extend that discomfort to thinking about how stakeholders might perceive such a request. Students, therefore, recommended that we employ the help of a professional facilitator. We ended up working together with our stakeholder participants as a single group in Study 3, with a researcher playing the dedicated role of facilitator throughout to keep the conversation moving and answer questions as they came up. Similarly, the facilitator in Study 3 was able to input the preference values into the tool, eliminating the 'tech' burden on groups.

Study 2 participants agreed that the group negotiation process give equal access, standing, and balanced influence to participants (63%). They also agreed that the group negotiation process laid the groundwork for trust-building amongst participants (63%) (Figure 51). Most (66%) also agreed that the group negotiation process encouraged learning amongst participants, and "the group negotiation was accessible; it made sense" (71%). Study 2 participants seemed to generally agree (63%) that the group negotiation process was well-suited to the specific application and simulated a real decision-making process. I interpret this not as a reflection that the group negotiation process was ready to share with stakeholders, but rather that students could see that it had promise or potential in 'real world' application (with a refined set of directions and additional facilitation, see section 5.3.2.). While many aspects of the workshop seemed to improve from Study 1 to Study 2 (based on participant evaluation responses), Study 2 participants were likewise critical of the model. Unlike their assessment of the group negotiation, most (~83%) participants did not agree that the model was accessible or made sense. Participants did not seem to think that the model was user-friendly (69% did not agree), robust (63% did not agree), or practical and well-suited to the application (~69%). In Study 2, less than half of participants (~40%) agreed that the decision problem analysis was intuitive and that the breakdown of the problem into decision criteria and alternatives was an appropriate choice for the model. Also, only ~32 percent agreed that the model was well-suited to the specific application. And, most (80%) participants did not agree that they would use a similar process in their own decision making. Only a slight majority of participants agreed that the decision criteria (~54%) and decision alternatives (~51%) were distinct, independent, relevant and meaningful to them, further indicating a need to enhance the salience of the decision problem in future DDSTs. The Study 2 post-survey evaluation results indicated to our research team that we needed to provide more information about the decision criteria and alternatives and find a way to clarify the criteria rating process (i.e., what were we asking participants to do and what did it mean to rate their preference for a criterion on a scale). These considerations drove us to prioritize DDST reorganization (e.g., 0 – 100 scale), as well as support material development (e.g., Decision Criteria and Alternative Description documents) and refinement (e.g., Dam Factsheets,) to enhance the instructional clarity and intuition for preference elicitation in Study 3.

Figure 51. Student post-survey responses to evaluation questions about different workshop components, Study 2 (n = 35)

Study 2 provided new lessons on UI/UX: mechanical issues became troublesome in DDST 2. Participants needed additional support (other than the tracker) making sure their slider bar inputs summed to 1. The 0 to 1 scale was challenging for some to interpret as percentages; participants wanted the scale to be 0 to 100. Participants also wanted simple instruction with more examples and less text. Like participants in Study 1, Study 2 participants were challenged by the preference elicitation process, and the actual calculation was opaque, with confusing MOGA-MCDA results (rose plots and maps that did not appear to coincide with preference values and there was no way to backtrack the calculation in the UI). In trying to reduce confusion and enhance understanding by separating the preference elicitation activity from the MOGA-MCDA calculation, we inadvertently made the DDST 2 into a 'black box'. Some additional reframing for process clarity would be necessary before use with stakeholders and DMs, especially in the group preference elicitation activity—using a Google Sheet was an intermediate solution, but it would be too confusing to implement with a group of DMs with varying levels of comfort with technology.

While students had limited practical background about dam decision making or hydropower, we were fortunate to have their expertise as a general audience. Not everyone knows about dams, so it was important to test the tool with a group of people who were less engaged with dam-related issues than FOD researchers or stakeholders/decision makers. Lessons from Study 2 include: 1) a need for additional decision context, 2) users expect a more intuitive UI, including better navigation and fewer written instructions. Students felt uncomfortable in rating criteria that were specific to dams they had little knowledge of, and little data to draw from. Dam Factsheets and Dam Data Tables gave some additional support, but not enough to make participants feel confident or comfortable with their decision-making. It was eye-opening to understand that UX/UI considerations were not limited to the tool's software program (i.e., a web-based app) and basic maneuverability (e.g., buttons, slider bars), but also in reducing the amount of reading necessary to use the tool, and making sure that users could follow along with the MCDA calculation. These findings prompted our team to reorganize the DDST 2 to DDST 3, to bring the MCDA front and center in the tool, and ultimately, to exclude the MOGA altogether (having run out of time before Study 3 to integrate it into the foreground of the tool as we had with the MCDA). While the participatory process and decision context in Study 2 was site-specific, the DDST 2 was developed to be generic, to accommodate future use on different dam sites. Written instructions informed users to consider individual dams. DDST 3 was modified to be site-specific, including maps, data, and embedded resource links (e.g., Factsheets) for site-specific context. We also improved the navigation between pages, adjusted the preference rating scale from 0 – 1 to 0 – 100, and were able to reduce the instruction text because of the model reorganization.

5.3.3. Study 3 Outcomes

In Study 3, it seems that we improved the criteria descriptions to a point where they were understandable to stakeholder participants. This may have been because we shared criteria definitions with participants ahead of time, but was most likely because we took the time in the workshop to walk participants through each criterion, discuss data collection or estimation, and answer questions about how we built our estimation models; we provided more prominent visuals to support understanding; and the participants started the process with a deeper understating of dam-related issues for FERC relicensing and some with prior knowledge of our MCDA research. In the researcher notes were a few short descriptions of participant interactions, highlighting the emphasis on criteria discussion early in the workshop:

> **Excerpt from researcher notes on 10/3/19:** Questions about where data about annual electricity generation came from, clarification on the number of properties impacted [criterion]:
>
> Tribal nation representative 3: *"Baseline is present conditions?"*
>
> Tribal nation representative 1: *"Disturbance is lack of waterfront property? How can that be a disturbance, isn't that a good thing?"*
>
> State agency representative: *"Isn't that a change? Not better or worse. Depending on perspective."*
>
> Federal agency representative needed clarification about what equal preference looks like: "*If you care about everything equally, but the outcome is different…"*

Non-profit A representative: *"It's because of the baseline data"*

During the property impact discussion, it seemed like a few participants thought that some criteria might be benefiting those who prefer current conditions (impoundments). A couple of questions were posed specifically to the regulatory agencies in the room (e.g. do they look at the systems perspective or single dams?)

Excerpt from researcher notes on 10/3/19: Participants seemed to need quite a bit of explanation in the "Introduction to MCDA section" to understand how the dam-specific baseline data and participant preference data interact to produce the delivered/ranked decision alternative outcomes. It seemed that confusion was building around 11:10 am, with several questions coming quickly and where the one participant seemingly let out an exasperated sigh. Soon after, when it was clarified that the outcome is partly driven by the dam-specific baseline data, the tension seemed to be relieved and participants began to nod their heads and seem to understand/accept.

Participants wanted more information or a clearer breakdown of decision criteria. This was expressed in post-survey comments from multiple participants, and noted by researchers observing the workshop conversation:

"I also think that the criteria that we discussed today could be either broken down further or better explained in the meaning and defining the items."—Private sector company representative

Excerpt from researcher notes 10/3/19: *"This ISN'T truly transparent UNLESS you understand the criteria. For sea run fish, you are looking at more math than 95% of the population has a concept of what that means. To call that transparent… If you go back to criteria, I am just looking at river recreation... you have great metrics but the real metric that counts the most is who is using it now?"—Non-profit B representative*

Excerpt from researcher notes on 10/3/19: Criteria—may be seen as too complex and not as transparent as it seems. You can share the equations but they may not be understood… *"Ambiguous decision criteria lead to ambiguous outcomes"*, issue with the CO2 emissions assumption – what will the hydropower be replaced by and would you really expect a complete loss in CO2 emissions offset? → This broadens the question into replacement [other generation technologies]…some users are reserved about this one because of that uncertainty.

The participants' points above are nuanced, but also important to highlight: the decision criteria were understandable, but not transparent. We can determine that decision criteria were understandable because as a group we were able to have rich conversations about measurement and data collection. And, in contrast to Studies 1 and 2, stakeholder participants were effectively able to consider decision criteria and share their preference ratings for each. In Studies 1 and 2, not all participants finished the activity and participants expressed much discomfort in the preference elicitation process (evidenced through post-survey feedback, individual DDST 2 notes in the case of Study 2, and researcher observations). The transparency issue arose when stakeholder participants began to consider how they might go about collecting these data for other sites or how to interpret results. Participants were not comfortable with the math behind the decision criteria data estimation (e.g., sea-run fish habitat area), and in some cases, they disagreed with how we elected to define the decision criteria (e.g., carbon emissions reductions based on the present fossil fuel mix avoided in generating renewable electricity from hydropower).

It became clear later in our conversation with participants that the pre-survey data generation also led to confusion in interpreting the preference elicitation for the social/qualitative decision criteria (e.g., indigenous cultural traditions and lifeways, aesthetics, and industrial historical value). This is confirmed in researcher notes:

Excerpt from researcher reflection meeting on 11/4/19: Social criteria caused a problem in interpretation, people felt like they responded to the survey two times, once at home and once in the workshop, because they had already answered questions about social criteria. Survey data collection so close to the workshop was problematic because the data values were confused with the preferences.

Excerpt from researcher notes on 10/3/19: Lots of discussion about the "community identity" criteria (and other social criteria). There did not seem to be agreement on what it meant and lots of confusion of what is included in that [criterion].

Participant lack of comfort was initially indicated in the numerous questions about decision criteria definitions from the introduction to MCDA given at the beginning of the workshop. We anticipated questioning by participants and developed a new series of posters to support this conversation (posters had not been included in the previous 2 workshops). The posters were set up around the room and acted as props for the facilitator. They also provided fodder for participant questions. The posters were something that engaged or curious participants could explore further during coffee breaks, giving them a sense of how the criteria metrics were developed or the data collected (as well as citations for our estimation equations).

In contrast to Studies 1 and 2, and despite some initial confusion or opposition to criteria measurements or definitions, participants seemed to think that that we offered them enough data to support them in their preference judgments (in contrast to the earlier studies). Participants worked through the tool with no additional critiques or complaints, and there were no comments about the slider bar ratings or decision scenario on the post-survey, so I interpret that as an indication that participants were clear about what was being asked about them and the tool was user-friendly enough to the point that there were few questions after the initial login process. From the outset, we asked participants to answer with their professional preferences (i.e., representing their group or organization) rather than their personal preferences, and to let their decision making be guided by mission statements, vision statements, or traditional cultural values where they were uncertain about how to balance tradeoffs. I would have expected comments about difficulty using the tool (as in the previous two studies) if user-friendliness or clarity was an issue, so I conclude that the individual process was in fact user-friendly. For instance, participants seemed to get stuck on MCDA model mechanics; specifically, normalization was an issue. On the post-survey, a federal agency participant highlighted a need for a greater explanation of the model:

> *"I think that it is very important to spend enough time to explain how the model works so that people understand how their preferences will impact the results. I found myself going back to the completed decision matrix to see the numbers and therefore see whether my preferences would align with my desired outcome. The direct connection was not always evident."*—Federal agency representative
>
> [relatedly, but in response to another open-ended question] *"I think there needs to be a clear understanding between Decision Matrix-Preferences and Outcomes. This is really where the rubber meets the road. If this is not well explained then it will cause confusion in all future dissuasions with the public."*—Federal agency representative

These post-survey comments point to normalization as a 'sticky' issue that concerned participants and likely contributed confusion about calculation. It seems that moving the MCDA model front and center in the DDST 3 helped some participants to understand the calculation (though some felt they needed to go "back to the completed decision matrix…[because] the direct connection was not always evident"), but others sought more explanation. Short of demonstrating the mathematical calculation as an interactive aspect of the tool (for instance, with 'live' changes to weighted criteria values and more advanced visualizations), bringing the MCDA model to the forefront was the most we could do to address 'black box' concerns during the course of the FOD project. At some point, users must trust the math and understand that the model is a representation of reality, based on a set of assumptions (statistician George Box's famous quotation, "All models are wrong, but some are useful" comes to mind, here). One of the observing researchers recorded the issue succinctly in their notes:

Excerpt from researcher notes on 10/3/19: [Non-profit B representative] made a point about their concern for the method for normalizing values…that if a value could still be improved on, it shouldn't get a score of "1" (presumably because that's the ceiling value beyond which improvement cannot be made). Another participant asked a follow-up question about normalization. [A member of the research team] expressed that normalization is quite complex, and that the goal was simplifying things a bit to accommodate the ability for users of model to fill in the limitations of the model (the model accommodating user preferences as a matter of making the model itself more robust). At 11:09am in response to the discussion of value normalization, [Non-profit B representative] said, *"I don't think this works, frankly . . . the things we've pointed out strike me as that some of this isn't valid in my mind."* [A member of the research team] thanked them for sharing this perspective and encouraged participants to address normalization specifically when they complete the post-survey, acknowledging that perhaps simplification may not be the best way to handle this and maybe it needs to be handled in a more nuanced way. This participant followed up with me during the lunch period to ask if this specific perspective had been recorded. They explained that they still had remaining concerns about how the value normalization was being calculated. I read them back the comment above, and they nodded and said that seemed like a good reflection of their perspective.

The idea behind normalization in MCDA is that criteria values are set relative to their range. So, while participants may not have felt entirely comfortable with the idea, it is how many MCDA approaches help the user to compare across decision criteria that would otherwise be disparate (analogous to comparing apples and oranges) without the need to value the criteria economically, as in a benefit-cost analysis. Max-min normalization allows us to handle criterion data relative to its range (0 – 1, where 1 is the maximum value) to be able to compare to other criteria values relative to their respective ranges. Relativity is the key concept. The idea that criteria values could theoretically be improved is irrelevant; if the criterion data value is the highest one in its range, it is set equal to 1. Normalization is the mechanism that allows MCDA to simplify a complex decision problem into something more digestible, because (as observed by the member of the research team identified in the excerpt above) the user of the model will imply whatever information they need to in their preference rating. The weight will then emphasize the normalized data value.

While our selection of normalization method was based on a thorough review of the literature (Ch. 4) and observations about DDST 1 and 2 UX, there are other approaches to normalization (e.g., vector normalization). We concluded that AHP approach (e.g., [183], [184]) and weighted product approach (used in Roy et al. [18]) were not appropriate for our purposes because we determined that they could confuse stakeholders about an already complicated MCDA process. We spent many hours as a research team in working through the math and making sure that we were all on the same page about AHP and weighted product mechanisms, effort which guided our shared conclusion that this could be problematic for stakeholders (reinforced by researcher observations and post-survey results from Study 1, which indicated that participants did not like or understand AHP). Future work might involve additional testing and specific assessment questions to evaluate the salience of different normalization approaches or instruction about the purpose of normalization in MCDA.

With the inclusion of raw data (Table 33), normalized data (Table 34), preference data (Table 35), and preference-weighted normalized (aggregated) data tables (Table 36), participants who were uncomfortable with normalization or the criteria definitions were able to move through the MCDA calculation step by step to prove to themselves how it was working. To support this self-guided exploration, the tables and figures each had interpretive guiding text explaining to the user what they were seeing and how to interpret it because graphs can be challenging to read if users are not accustomed to doing so. So again, while the methodology was not something that everyone was fully comfortable with (based on my experience, this is true for some people with economic valuation methods as well), participants could understand and follow what was going on. Participants could see the data at each step in the process (recall that we excluded the MOGA portion of the model from DDST 3) and move back and forth from the user preference inputs to the graphed results. Finally, participants perceived the graphed results (Figures 45 – 49) as believable. They could see how their preference inputs shaped the graphed results, and the tables (Tables 33 – 36) allowed some level of traceback through the calculation.

Table 33. Study 3: Raw, site-specific data for West Enfield Dam (social criteria are not included here because the table was too long).

	FishHabitat	RiverRec	Reservoir	ProjectCost	BreachDamage	NumProperties	ElectricityGeneration	AvoidEmissions
Remove Dam	86750	19	0	179	0	5	0	0
Improve Fish Passage	55480	12	0	1067	2	0	73	10
Improve Hydro	24200	12	0	949	2	0	73	10
Improve Hydro AND Fish Passage	55480	12	0	1067	2	0	73	10
Keep and Maintain Dam	24200	12	0	949	2	0	73	10

Showing 1 to 5 of 5 entries Previous

Table 34. Study 3: Normalized criteria data (on a scale of 0-1) for West Enfield Dam (social criteria data not included because the table was too long).

	FishHabitat	RiverRec	Reservoir	ProjectCost	BreachDamage	NumProperties	ElectricityGeneration	AvoidEmissions
Remove Dam	1	1	0	1	1	0	0	0
Improve Fish Passage	0.5	0	0	0	0	1	1	1
Improve Hydro	0	0	0	0.13	0	1	1	1
Improve Hydro AND Fish Passage	0.5	0	0	0	0	1	1	1
Keep and Maintain Dam	0	0	1	0.13	0	1	1	1

Showing 1 to 5 of 5 entries Previous

Table 35. Study 3: Elicited criteria preference scores (on a scale from 0-100) from DDST 3 using group average preferences.

Sea-Run Fish Habitat Area	41
River Recreation Area	6
Reservoir Storage	6
Annuitized Project Costs	3
Breach Damage Potential	7
Number of Properties Impacted	3
Annual Electricity Generation	6
CO2 Emissions Reduction	6
Indigenous Cultural Traditions and Lifeways	17
Industrial Historical Value	1
Community Identity	1
Aesthetic Value	1
Public Health	2
Socio-Environmental Justice	1

Showing 1 to 14 of 14 entries Previous 1 Next

Table 36. Study 3: Preference-weighted criteria scores for individual decision criteria and alternatives at West Enfield Dam (based on group average preference, Figure 54).

	FishHabitat	RiverRec	Reservoir	ProjectCost	BreachDamage	NumProperties	ElectricityGeneration	AvoidEmissions
Remove Dam	40.6	6.1	0	3.3	6.7	0	0	0
Improve Fish Passage	20.3	0	0	0	0	3.3	6.1	5.6
Improve Hydro	0	0	0	0.4	0	3.3	6.1	5.6
Improve Hydro AND Fish Passage	20.3	0	0	0	0	3.3	6.1	5.6
Keep and Maintain Dam	0	0	5.6	0.4	0	3.3	6.1	5.6

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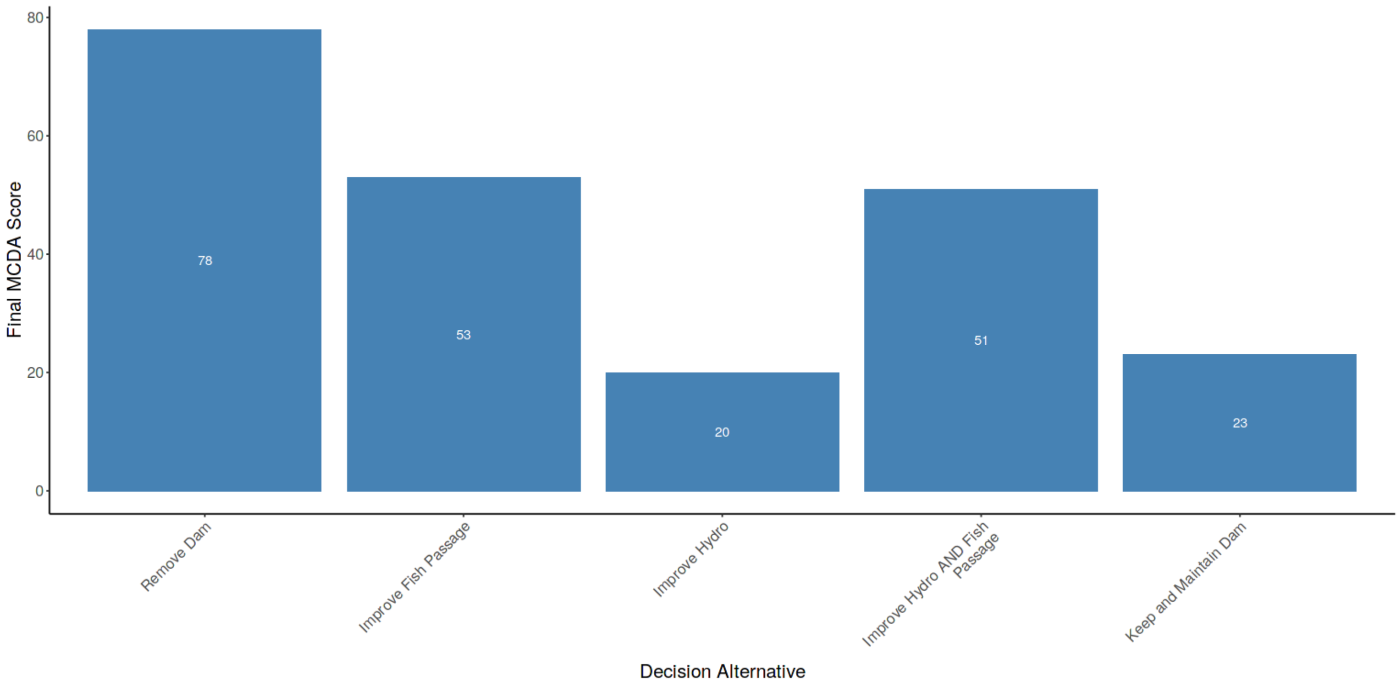

Figure 52. DDST 3 single-dam results graph (group averaged preferences) for final MCDA at West Enfield Dam.

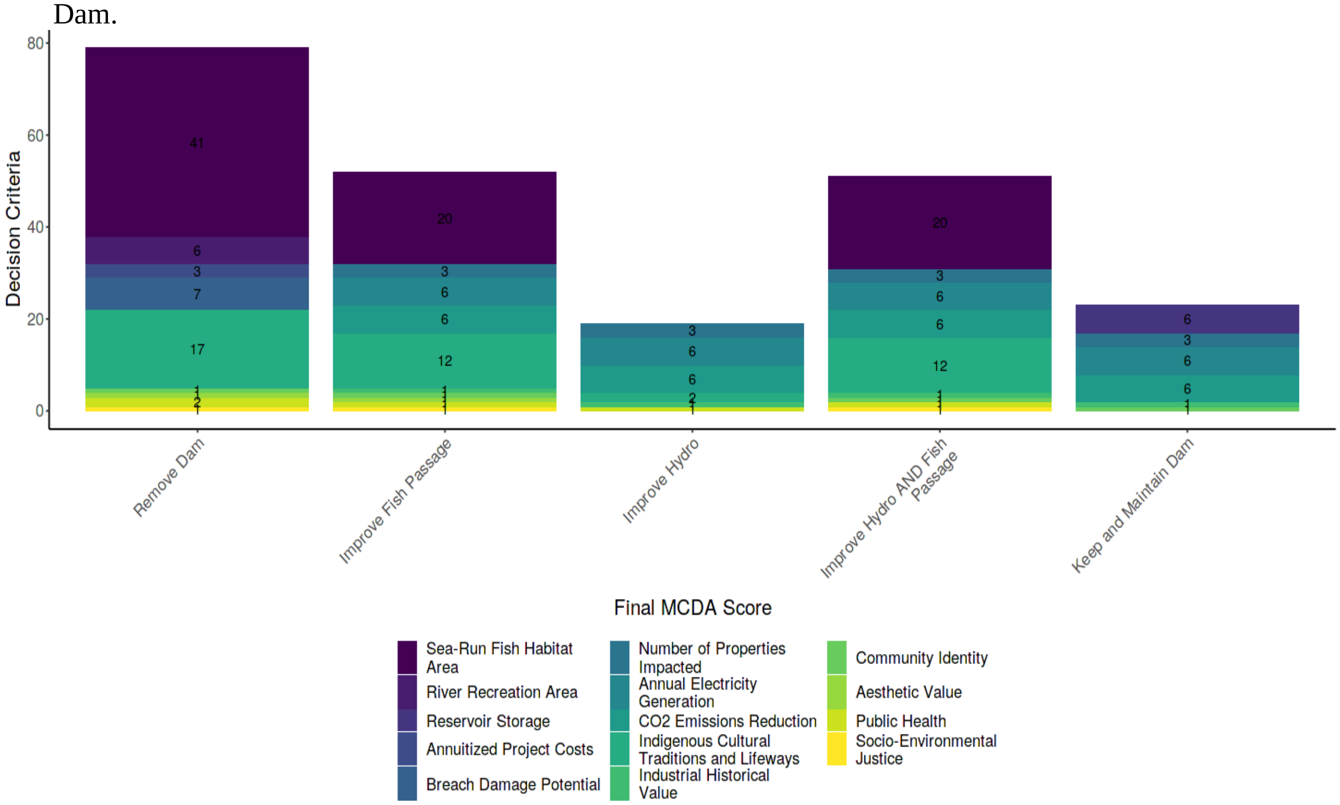

Figure 53. DDST 3 criteria breakdown of final MCDA results for West Enfield Dam (again using group averaged preference ratings).

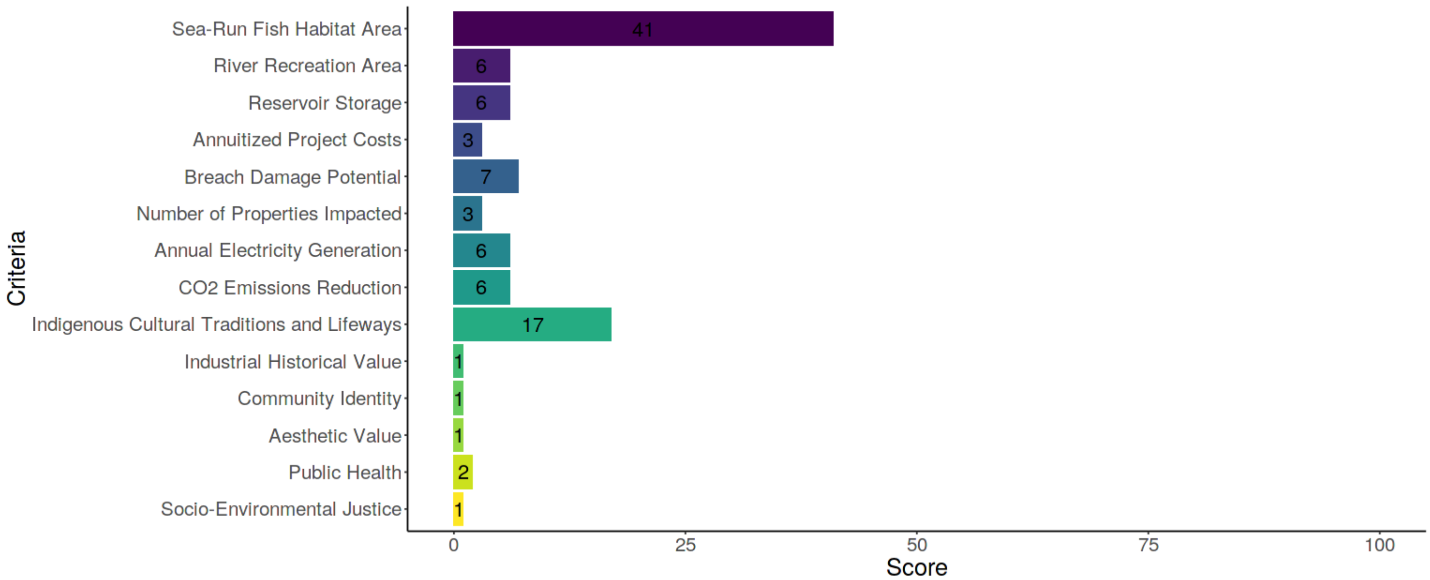

Figure 54. DDST 3 individual criteria preference input values (averaged group preference ratings or 'scores') compare with Figure 46 (DDST 2).

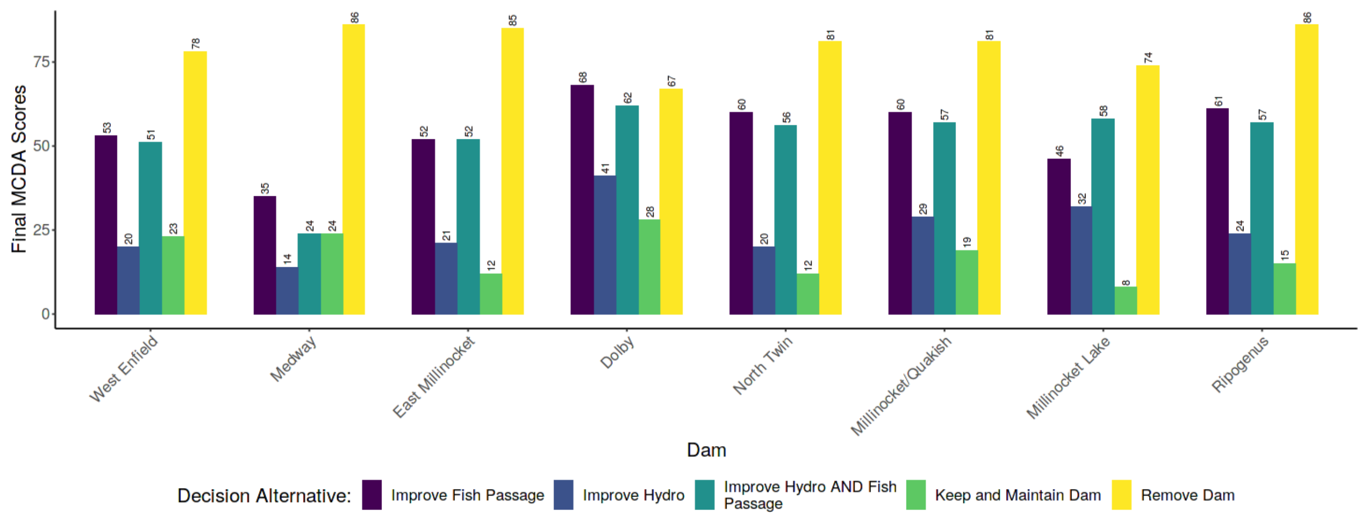

Figure 55. Example of DDST 3 multi-dam final MCDA results (group averaged preferences), where the tallest bar indicates the recommended decision alternative at each dam. Note: the multi-dam results aggregate single-dam outcomes and do not take into consideration what is going on at each of the other dam sites.

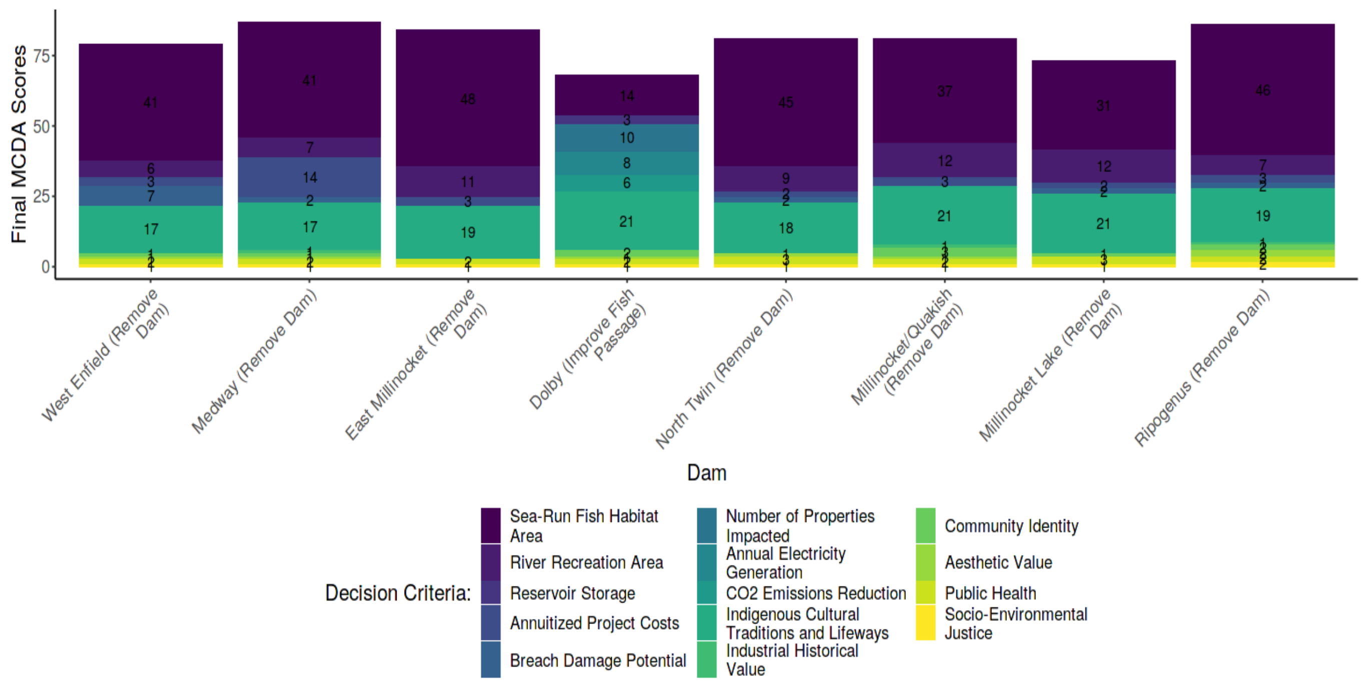

Figure 56. Top-ranked decision alternative at each dam, broken down by criteria (based on average group preferences). Note: the multi-dam results aggregate single-dam outcomes and do not take into consideration what is going on at each of the other dam sites.

The group activity, which focused on West Enfield Dam for brevity and involved deliberation over shared preferences (using the non-weighted average of individual preferences as the starting point for conversation), yielded some interesting results in terms of participant leadership. While participants were instructed to work toward compromise, it became apparent during the group discussion that consensus was not going to be possible within the time remaining in the workshop. The difficulty in finding agreement was relating to one criterion in particular: sea-run fish habitat area, where the averaged individual preference rating was 41 ‘points’. When the facilitator (Dr. Klein) led a vote, 6 people thought that the value seemed low, 3 people agreed the value was fine, and 1 person thought 31 was too high.

Excerpt from researcher notes 10/3/19: [Dr. Klein] asked about whether people would feel comfortable having the marker moved 50. About 50% raised hands. [Dr. Klein] asked if those who are not comfortable moving the needle from 41 to 50. When asked about AT LEAST 50, fewer people raised hands. When asked about 40%, one person raised their hand. [Dr. Klein] asked people would want to say something to make a case to support their number.

One of the observing researchers pointed out the collinearity of tribal preferences for the indigenous cultural traditions and lifeways criterion and the sea-run fish criterion. The researcher emphasized the fact that these are challenging to disentangle from one another, and in trying to do so, both criteria had fewer preference points allocated toward them. A tribal nation participant shared some thoughts about this collinearity:

> **Excerpt from researcher notes 10/3/19:** *"Sea run fish is important to the culture of the tribe. That's what they historically used. There is more to the culture that sea run fish. Some of them are not tied to dams or the river. There are upland species. It's the fish and the connection to those fish. To those resources in the river. The relation between the tribe and water."*
>
> –Tribal nation representative 3
>
> *"The cultural is VERY important to me but I can't make YOU feel that way. Sea run fish – if they come back our culture will be stronger. I will give that one more point than the cultural piece because I don't believe everyone will give it that same amount. SO, if I give sea run fish more point and if they come back, our culture will be stronger."* –Tribal nation representative 1

The idea was that including two separate decision criteria, one for indigenous cultural traditions and lifeways and another for sea-run fish habitat area actually created a false dichotomy for the decision maker when going through the UI and rating criteria.

> **Excerpt from researcher notes 10/3/19:** *"If sea-run fish are restored, cultural lifeways are restored."*
>
> –Tribal nation representative 1
>
> Note: this comment ended up shaping the discussion from here on out. Consensus-building around fish passage is a way to make sure that indigenous cultural traditions and lifeways

get protected in a way that gets other groups and organizations on board and throwing their resources into the conversation in a very different way.

Essentially, one of the tribal nation participants shared that the focused rhetoric around sea-run fish restoration would restore cultural lifeways relating to fish, as well as bring more money from NGOs and more support from federal agencies with fish-related missions, as we saw with the Penobscot River Restoration Project. The participant who shared their strategic thinking around their decision to give the sea-run fish criterion more preference points to achieve the desired outcome may have inspired strategic thinking for other participants. A similar conversation was started around community identity vs. indigenous cultural traditions and lifeways, which were likewise perceived as collinear by some participants:

Excerpt from researcher notes 10/3/19:

Tribal nation representative 1: *"Me being native, I was always answering the scenarios from my point of view as part of the community because I look at the river as a sister so I would always put myself in the community no matter where I am in the watershed."*

Tribal nation representative 4: *"I also thought about this when ranking community identity because the fish really matter but there are also sacred sites up there further in the watershed that our ancestors probably used."*

Tribal nation representative 1: *"But I didn't rank community high because the community is a melting pot. They don't all see eye-to-eye so I thought fish would be more important to rate high."*

Later on, a state agency representative asked about the particular focus on consensus, because there were a few sticking points (like sea-run fish habitat vs. indigenous cultural traditions and lifeways) in discussion, and they saw an opportunity to reach a potential compromise.

Excerpt from rsearcher notes 10/3/19: In return to the question of which sliders could be moved (around 3:10 pm), a [state agency] participant suggested that the group identify if they could reduce points in several of the lowest-rated categories so they could redistribute them elsewhere. There was consensus to do so, and in response another participant congratulated the participant that had suggested this for their success in building consensus, and how it spoke well for their work in their position.

Excerpt from researcher notes 10/3/19: [State agency representative] proposed to look at metrics that people care less about and see if the group can take points away. The group dropped public health, industrial history, and aesthetics to zero. That gave more points to other metrics that are of importance.

Non-profit representative: "*Would [Tribal Nation] folks trade some of the indigenous cultural points for an increase to fish?"*

Tribal nation representative 1: *"I would."*

The group decided to remove 17 points from indigenous and add it to fish, in the interest of reaching consensus.]

After observing the stagnation in conversation around preference point allocation, the state agency representative ended up stepping in and suggesting that facilitators refocus the group discussion, around compromise. This suggestion started the conversation around preference points allocation back up, and participants were able to achieve some agreement about shared preferences for decision criteria and see a final recommended outcome for the West Enfield Dam based on their shared preferences (Figure 52). The failed consensus and the preceding discussion about strategic voting with regards to sea-run fish habitat area created an opportunity for compromise. The conversation about strategic point allocation and where preference value had the most impact was an unexpected outcome of the shift from consensus-building to compromise-seeking (Figure 57). The research team observed evidence of learning amongst participants in these rich conversations about perspectives and priorities for river-related decision criteria.

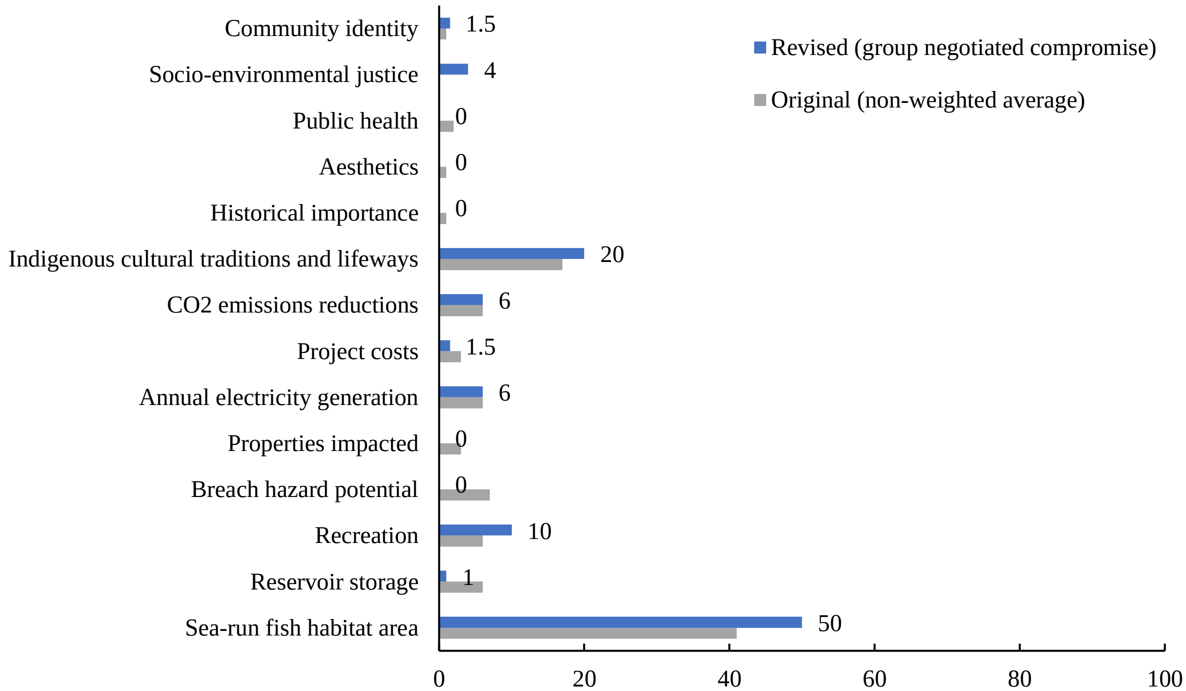

Figure 57. Group discussion-based changes in shared preference ratings for criteria at West Enfield Dam.

All (100%) of our 9 Study 3 participants filled out the post-survey, most likely because we set aside time for it at the end of the workshop. And, I followed up individually with the two participants who used the time at the end of the workshop to chat with researchers instead of filling out the survey. In general, Study 3 participants liked the new materials and workshop design/activities (Figure 58). Everyone (100%) "somewhat liked" or "liked a lot" the posters of decision criteria, alternatives, and site-specific dam posters (each with a Dam Data Table and Dam Factsheet information) posted around the room. The facilitation (~78% "liked somewhat" or "liked a lot") and overall experience (100% "liked somewhat" or "liked a lot") also fared markedly better in Study 3 than in Study 2. And, by a show of hands, we opted not to go through the preference rating process for all of the dams as a group, sticking to West Enfield Dam because its relicensing process is already underway. Study 3 participants were more amenable to all aspects of the workshop, with ~67% reporting that they at least somewhat liked the material or activities. The Dam Data Tables received mixed reviews. One person reported disliking the group activity a lot, as well as the DDST 3 and the results presentation (DDST 3 and results presentation also received neutral reviews). One person also reported disliking the individual activity and the Dam Factsheets. When compared to Study 2 (Figure 49), these results appear to be more positive overall, with mean Likert ratings 3.5 or higher.

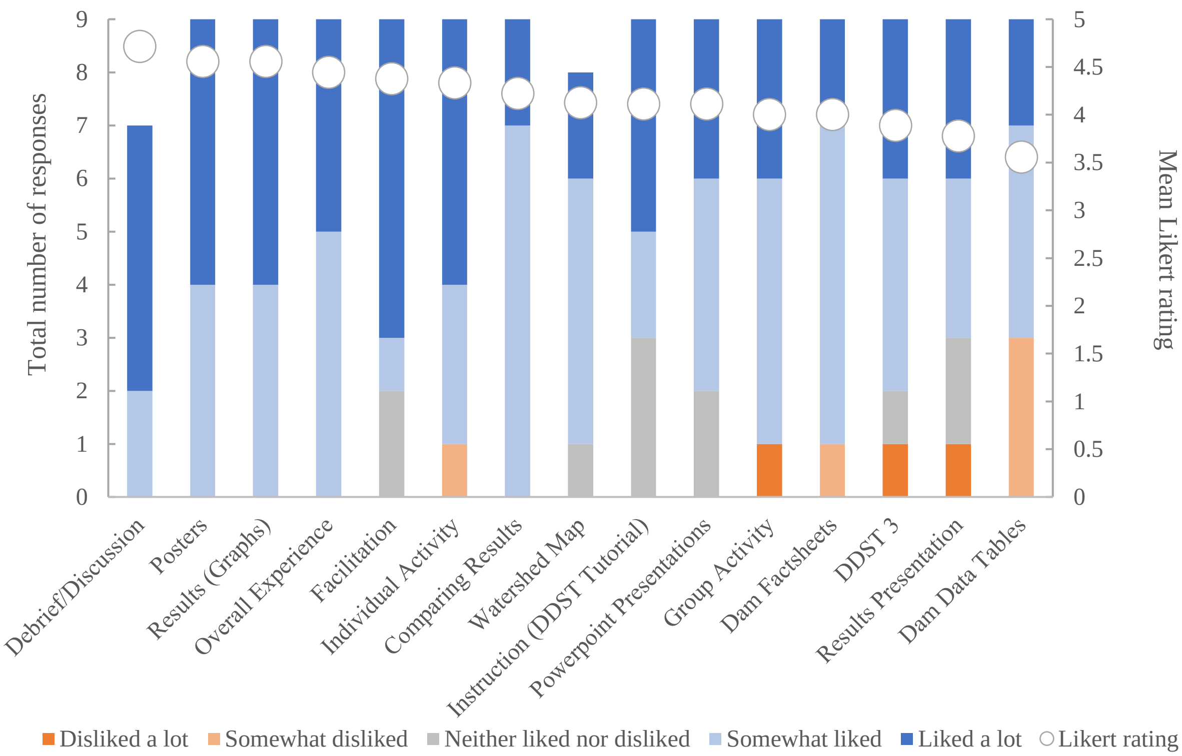

Figure 58. Study 3 Participant responses to the question: how much did you LIKE or DISLIKE the workshop materials/activities? (n=9).

Reported learning (i.e., learned something or learned a lot) was also higher in Study 3 (Figure 59). A total of ~87 percent or more of participants said they "learned something" or "learned a lot" from all workshop materials and activities on the post-survey. Participants most reported learning from debrief/discussion (70%), posters (100%), and graphed results (100%) received the greatest overall positive response, followed by the individual activity (100%) and comparing results (100%). Though participants seemed to like the overall experience (see Figure 58), one participant was honest in their review that they did not learn anything new. Facilitation, group negotiation activity, Dam Factsheets, DDST 3, results presentation, and Dam Data Tables likewise received a single critical review in terms of learning.

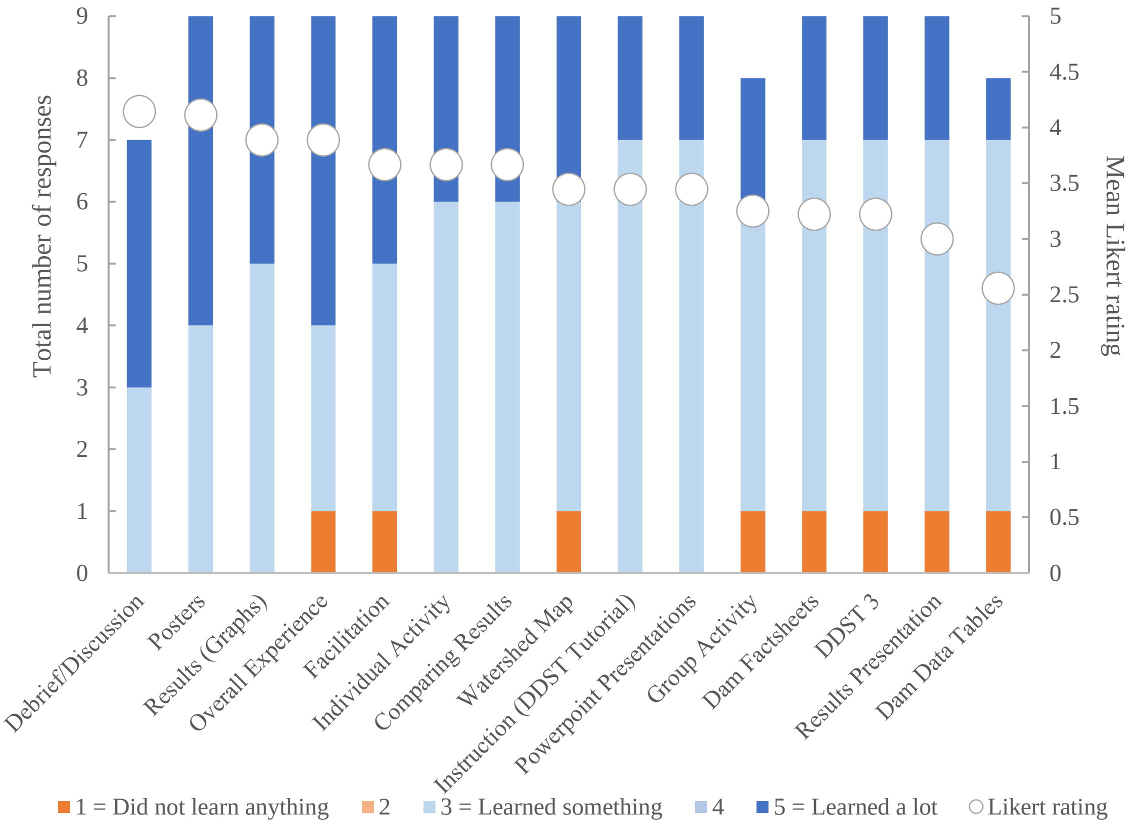

Figure 59. Study 3 participant responses to the question: how much did you LEARN from the workshop materials/activities? (n=9)

Researcher observation notes were absent of explicit commentary that participants evidenced learning, but more than one researcher on the team saw evidence that learning was happening (observation shared via informal peer check-in). In particular, peer-check in identified that there was a key conversation where learning about renewable energy was observed: in the conversations about CO_2 emissions reductions, participants were reminded about the importance of the load-following capabilities of hydropower (in contrast with the characteristic intermittency of generation wind and solar), and learned about the problem in assuming that removal of active hydropower resources from the electricity mix will be replaced by other renewable energies. It was important to test the DDST 3 with a group of people who could attest to its usefulness in supporting planning or discussions about FERC hydropower relicensing, to ground-truth the tool with potential ‘real world’ users, so while we were not specifically looking for evidenced participant learning about decision criteria or alternatives about which they have expertise, in this instance we did see learning about renewable energy.

Despite some existing professional relationships and a general awareness about other participants' groups, Study 3 participants also appeared to gain additional depth of understanding about one another's agency/group missions and values, management priorities or tradeoffs their group considers regularly, and different groups' roles in the FERC process. In particular, the conversation about preference 'point' allocation between sea-run fish habitat area and indigenous cultural traditions and lifeways criteria showed clear evidence that non-tribal citizens learned about what is most important to tribal citizens. The general assessment that participants learned from one another is a workshop outcome that positively links with the research goal about enhancing participatory capacity. Strategizing about priorities in common and raising awareness about how different groups consider tradeoffs are forms of capacity-building activity.

Whether or not they liked or learned from the DDST, workshop materials (Dam Factsheets, or Dam Data Tables), or group negotiation activity themselves, stakeholder participants did spend some time brainstorming (during the debrief session) about how the DDST could be useful to others. An interesting result was that some participants expressed that they could see others benefitting from the DDST and group negotiation process:

Excerpt from researcher notes on 10/3/19:

Federal agency representative: *"Thinking about this process and doing it early about the [dam name removed] project. It's a total mess. There were some factions that didn't have the same basic info and weren't talking at the same level. Those camps committed, today 3-4 years later, and they are just not talking to each other. Early on, if they had an opportunity to have a process like this, it would have been much more of a discussion because they would have had the same info from the start, and they might be at a different point."*

Private sector company representative: *"To get the ball rolling from the beginning. You can snowball them a little bit."*

Federal agency representative: *"Originally, I said it may not be a big change from what I do. But the [dam name removed] process…"*

Researcher: *"Would you recommend trying this out with a general public audience?"*

Federal agency representative: *"Yeah. It would be totally different, and I think you would learn a lot."*

One participant pointed out that the DDST could be used to spark early discussions in other, real dam decision making processes. The participant seemed to think that shared information could solve some problems, that by getting people "talking at the same level" or by having access to "the same info from the start", some of the contentions might be avoided. This phrasing is consistent with the language our research team has used in the past to describe MCDA to people (other researchers, University press) unfamiliar with the concept. This observation from participants was a key outcome that appears to indicate that the DDST 3 could be useful, provide information access, and build capacity for participation in relicensing. The excerpt from the researcher notes shows that the participants are thinking about how to use the tool in their work or encouraging others to use it to avoid long-term conflicts in dam decision arenas.

Dam owners were a notable absence in the room, which was important in the discussion of results and feedback from participants. Participants seemed to think that dam owner perspectives could have changed things in the group discussion, and this may be true. Participants predominantly expressed fish and tribal interests, and there was no dam owner or municipal representative to represent those perspectives. Representation was in fact skewed, despite our research team's efforts to balance diversity of interests with our workshop invitations. Last-minute changes to the participant roster (i.e., participants emailing about scheduling conflicts or illness) contributed to this as well. From participant post-survey comments:

> *"I think that it would be important to get the hydro owners involved (understanding that it has been difficult to contact them), but I believe that they would be a very valuable voice to the process."*—Private sector company representative
>
> *"I was not stunned that industry refused to participate. What does that tell you?"*—Tribal nation representative 3

Researchers underscored this noted absence in their notes, and observed the impacts it had on group dynamics:

> **Excerpt from researcher notes on 10/3/19:** Full-group introductions: [Licensee] was specifically mentioned but I don't believe their perspective (or that of any hydropower company) was represented in the participants present at the workshop.
>
> **Excerpt from researcher notes on 10/3/19:** Definitely seems to be some tension in the room when discussing hydro owners and operators and some tension about them not being here at the workshop today.

This result was not unexpected, but not for lack of outreach. We contacted dam owner representatives multiple times and received requests for more information in return, but no actual confirmation of intent to attend. The need for owner participation in 'real' decision-making became exceedingly clear when we showed the example mapped result that could have come out of the workshop (Figure 60), had the research team been able to integrate the MOGA successfully in time. There was much confusion about what the example MOGA-MCDA map was representing, particularly because the indicated result at each dam site (i.e., ‘Keep and Maintain’) was the opposite of the group’s negotiated outcome, which generally suggested dam removal (6/8 dams) or fish passage improvements (2/8 dams) as possible decision alternatives for the dams in the set. Participants expressed to the research team that their shared MCDA result was likely not a realistic outcome that could be achieved with hydropower dam owners in the group, and that it would have been interesting to see the mapped result after a ‘real’ discussion with dam owners at the table, too. The research team made it clear that we had run out of time to integrate it into the DDST and would likely not have the time to do so in the future, nor was it likely that we would do another workshop with dam owners present.

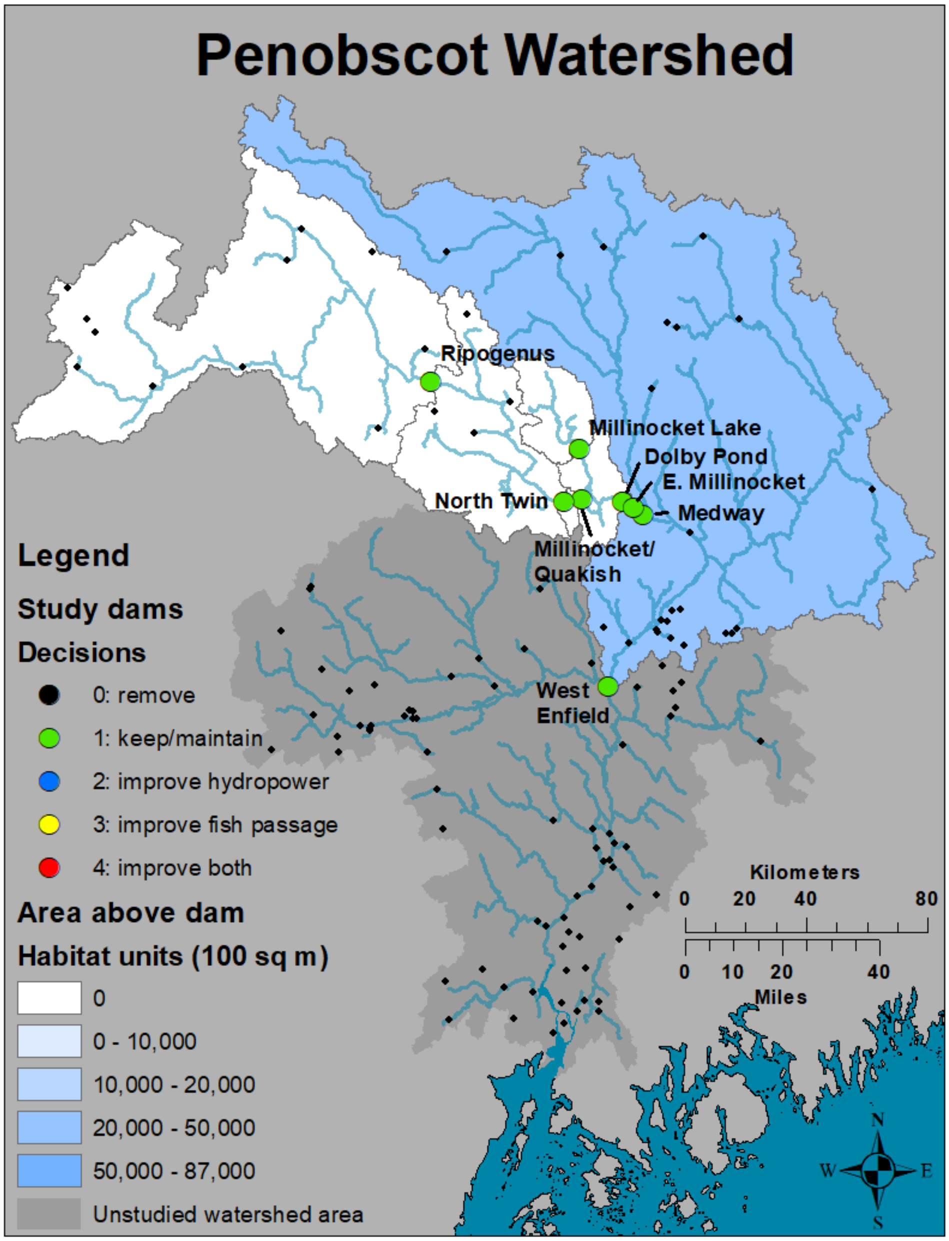

Figure 60. Study 3: Penobscot watershed map originally designed to be included in the DDST before the MOGA had to be eliminated. Example result given status quo (i.e., 'Keep and Maintain', where dams stay in place, with no significant changes to hydropower or fish passage).

Ultimately, participants had positive things to say about the participatory process. Despite a negative assessment of the model on the specific post-survey evaluation questions (section 5.3.4), participants shared feedback about the (albeit qualified) 'success' of the model:

“Thanks for all your hard work. Don't be discouraged by critical comments. Your tool is excellent. The challenge is utilizing the tool in the present hydro management system.”—Tribal nation representative 3

“I feel this is a great initial model to build on, it provides a structure around these difficult conversation[s] that should be useful when developing these projects.”—Non-profit A representative

“This is an awesome project! I can tell you guys worked hard to get where you are and you effectively communicated an important part of science and decision making.”—Tribal nation representative 4

In general, participants seemed to understand that the DDST is a potential aid for participation in a complicated hydropower dam process, synthesizing data for several key scientific criteria and supporting further conversation. We emphasized the fact that the DDST remained a work in progress, and that it would never be a replacement for DM critical thinking; rather, it was intended to help DMs analyze their tradeoffs and priorities alongside site-specific data.

We also recorded written notes on large poster paper during the Study 3 group discussion/debrief to better capture (in participants’ own words) the general sentiments about the usefulness of the DDST. Participants were interested in the possible uses of the DDST and saw potential merits of the DDST in early stages of relicensing discussion to engage the public in “what the future of their rivers should look like”. While the decision criteria (annotated as DC in Figure 61) were considered incomplete or in need of some additional revision (as noted previously), due to concerns about appropriateness for “the average Mainer”, participants also agreed that the DDST was “thought-provoking” and could help put “issues out upfront” of the FERC process.

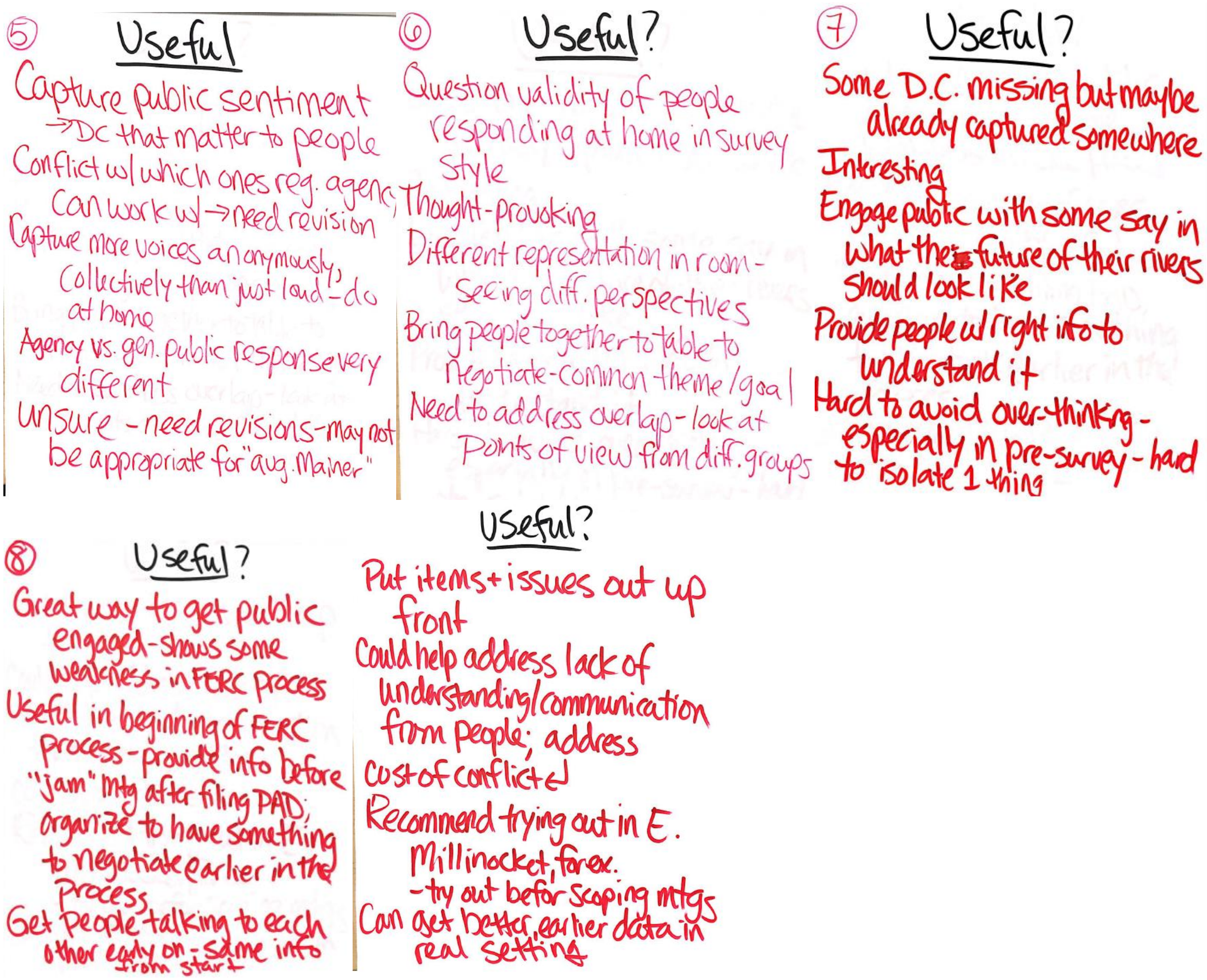

Figure 61. "Live" notes taken during the debriefing of the group negotiation process, Study 3.

Study 3 participants offered positive evaluations for the environment of respect (100% agreed "other participants in the workshop showed respect for my ideas and contributions"), learning (~78% agreed "I gained new knowledge in the workshop that I didn't have before"), and self-expression (100% agreed "I felt like I could express myself with ease throughout the workshop") that were fostered in the workshop (Figure 62). As in other studies, stakeholder participants were more critical about the model. While a majority (~89%) of participants thought that the model seemed to have been developed based on stakeholder input (it was), fewer people (~67%) responded that they "could see how the model presented in the workshop could be used in real-world applications". Fewer still (56%) thought that "the outcome was realistic, useful, and it could be made actionable" or that "the outcome is possible within regulatory constraints" (45%). Overall, participants were most critical of the decision criteria, where ~56% of participants disagreed that the criteria were accurate, ~56% did not agree that "the decision criteria were both relevant and meaningful to me". A strong majority (89%) thought that the set of decision criteria included in the model *did not* represent the full set of priority issues surrounding the decision to be made. The overall model accuracy was an issue (only 56% agreed that it was accurate and made sense). Also, most (~78%) of participants did not agree with the model clarity ("It was clear in the model how user preferences were combined with underlying data and calculations to result in an outcome"). Finally, a lack of diversity was a major critique of the workshop, with ~78 percent of participants responding that they disagreed with the following statement: "The mix of people at the workshop represented the appropriate level of diversity of perspectives and was represented in the top priorities". As discussed in section 5.3.3., the hydropower dam owners were missing from the conversation, and participants were fully aware of the fact that actual negotiations in a dam decision-making process would not come to fruition without the licensee present.

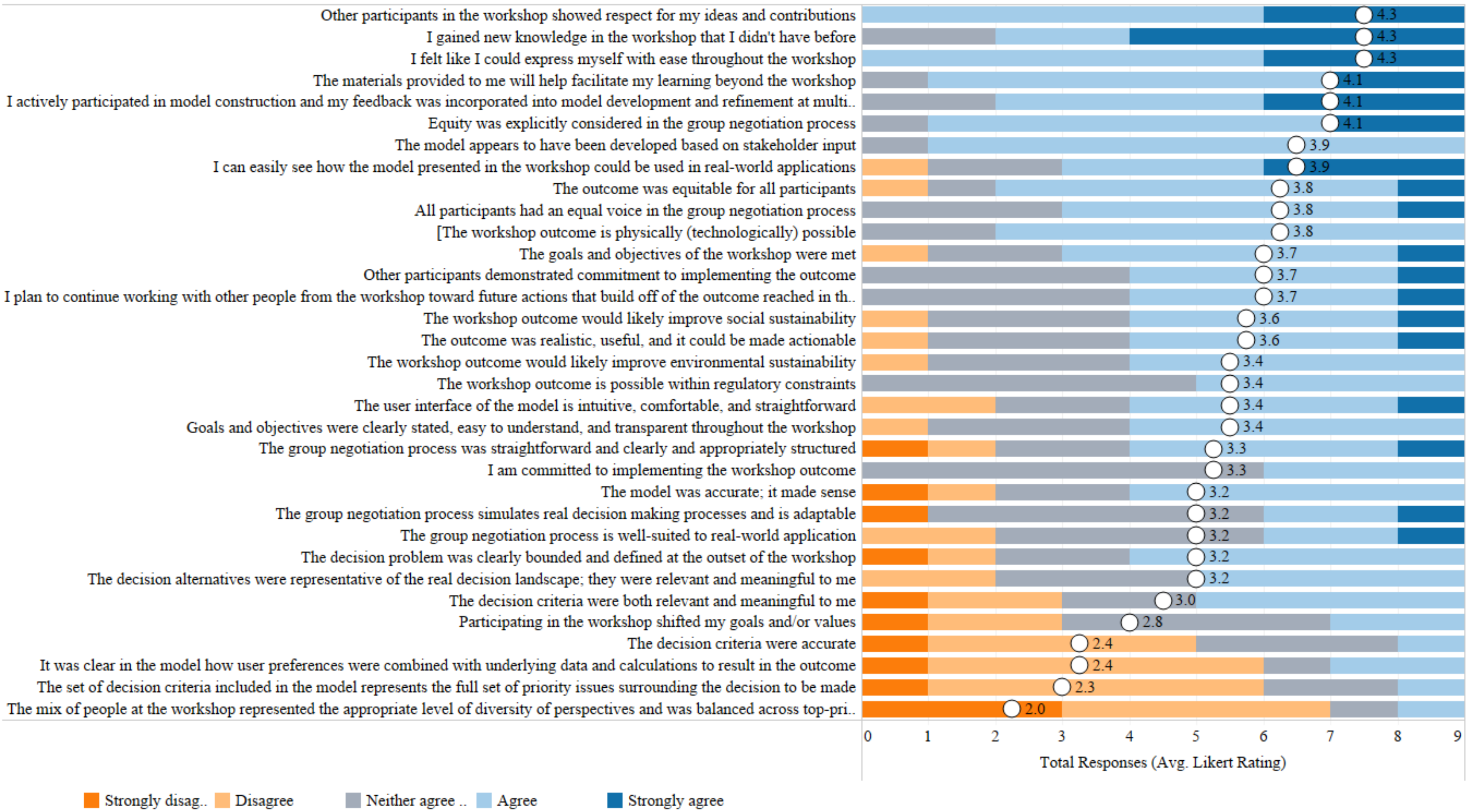

Figure 62. Stakeholder responses to questions evaluating workshop components, including outcomes Study 3 (n=9).

Testing the DDST with DMs identified a new set of lessons. First, aiming for consensus might overshadow potential opportunities for compromise. One DM participant showed great leadership in identifying this oversight and steering conversation toward compromise at the end of the workshop. This participant 'saved' the group negotiation process by recommending a new approach to achieve an actual outcome of the group activity portion of the workshop, despite original instruction to seek consensus. Second, adaptability made the difference in participant understanding of the model. We took an extra hour to go over decision criteria and alternative descriptions, discussing data collection and sharing citations/reading materials. This shortened the time set aside for other activities, but it gave time for clarifying questions, so while ultimately a few stakeholders left feeling as though the model was not transparent, participants did understand what was going on with the calculation and what was being asked of them in preference elicitation. While it did not necessarily enhance buy-in of the model as-is, researcher responses to participant questions demonstrated that the team made significant efforts in data collection and estimation for different decision criteria (e.g., annuitized project cost, CO2 emissions, sea-run fish habitat area). Study 3 also revealed new and necessary changes to be made before the public release of the DDST. The research team agreed to cut the social decision criteria that DMs critiqued as 'falsely dichotomizing' in the group negotiation activity (public health and socio-environmental justice were two criteria mentioned as problematic in this sense), and committed to describing a list of limitations for interpretation of MCDA results. For example, some decision criteria must legally be considered in the process, so while a user could rate its importance as 0/100 on the slider scare, sea-run fish habitat area is a factor which will legally be considered as highly important in rivers with endangered migratory species, such as Atlantic salmon.

5.3.4. Comparative Cross-Study Results

In this section, I consider results from all three studies but focus on Studies 2 and 3, which are more easily comparable due to the DDST outputs (i.e., graphs) and post-survey similarities. In general, participants in all workshops seemed to acknowledge and appreciate the purpose of each activity (group, individual, and single or multi-dam decisions). Note: Study 1 did not include an explicit survey question for cross-comparison, group vs. individual participant MCDA activities. Most (~78%) Study 3 participants preferred both group and individual MCDA activities equally (Figure 63). Despite the lengthy group data entry process (recall: in DDST 2, students entered their own individual preference values into an Excel worksheet shared by the group to calculate a group average, a process that was automated in DDST 3), a majority (~57%) of Study 2 participants preferred the group MCDA activity to the individual activity, while ~26% of Study 2 participants preferred both group and individual MCDA activities. A single participant in each study did not like either activity, which I interpret as an indication of dissatisfaction with some aspect of the workshop, most likely the DDST, individual/group activity instructions, or individual/group activity facilitation (all of which participants indicated mixed feelings about in response to "How much did you LIKE or DISLIKE the workshop materials/activity?", sections 5.3.1. – 5.3.3.).

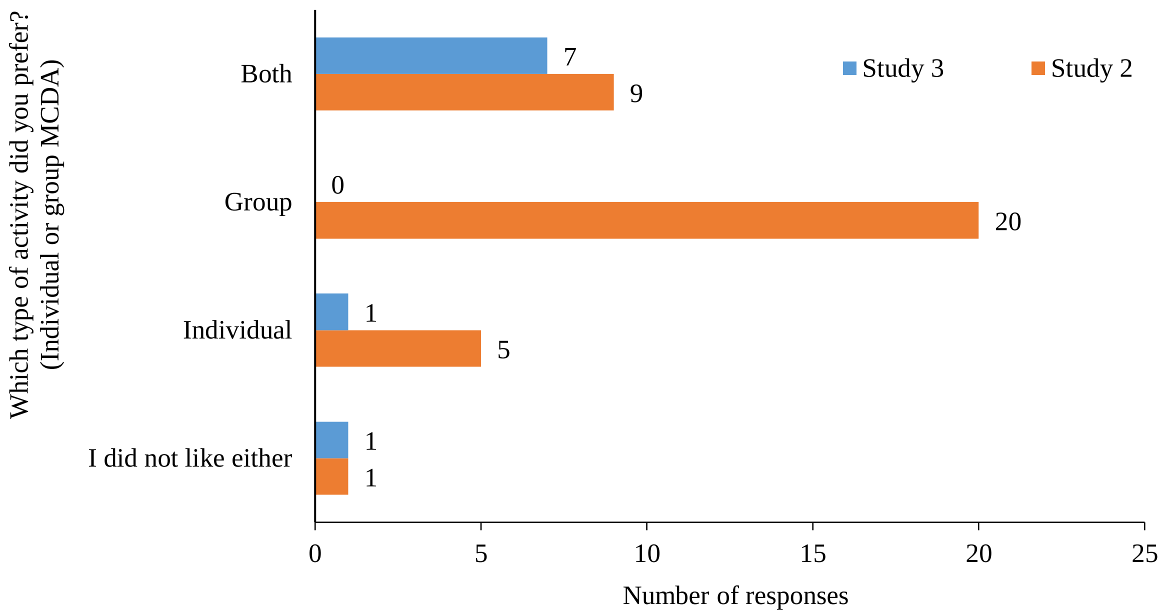

Figure 63. Responses to the post-survey question: Which type of activity did you prefer (individual or group MCDA)? Recall, the question was only asked in post-survey for Study 2 (n = 35) and Study 3 (n = 9).

Post-survey responses to the open-ended "Why?" after the question about individual vs. group activities (Figure 63) gave some additional information to help me interpret student (Study 2) and stakeholder (Study 3) participant perspectives. In the post-survey for Study 2, student participants said:

> *"I think that there are benefits of giving opinions both by yourself and with a group."*
>
> -Student

> *"I thought that both had value. Doing [the MCDA activity] individually allowed us to have a base knowledge while discussing and doing this in a group allowed us to hear why people chose specific values for different criteria."* -Student

Overall, the survey results indicate that Study 2 participants preferred the group activity, but my sense of this result is that much of it related to the lack of introduction to MCDA before performing the individual activity (recall: participants in Study 2 used the DDST alone, before the group workshop). Student participants were not confident about how they were supposed to rate the decision criteria, whether they were supposed to be answering from their own perspective or answering while imagining themselves in a stakeholder's position. In the Study 3 post-workshop survey, stakeholder participants said:

> *"I think it is important to get your own views (organizations) down first and then work with other to get a combined approach*."—Private sector company representative
>
> *"I liked the individual learning so I could better understand the model but the group to better understand how the different inputs to the model and how they varied with the discussion."*—Federal agency representative
>
> *"I think both were important. Individually helped me consider my desired preferences; the group work helped me understand other people's preferences or questions and comments."*—Tribal nation representative 2

In both studies, participants saw a purpose for the individual activity in establishing "a base knowledge" or helping to "get your own views first", while the group work was generally perceived as a layering on of perspectives or exposure to the preferences and questions other people were grappling with. This kind of sharing or exposure to others' priorities can be seen as an indication of potential for the tool in capacity-building and is the main impetus behind doing a group participatory MCDA. With individual MCDA, the DM can get a feel for their own priorities, but with group participatory MCDA, there are others' viewpoints to consider and along with that, the possibility of learning from one another and expanding one's own worldview. Recall, in all 3 studies, the debrief/discussion scored high (mean Likert response between 3.5 and 4) in the post-survey questions about learning. When asked: "How much did you LEARN from the workshop materials/activities?"

Studies 2 and 3 were designed to compare the experience of single and multi-dam decisions after Study 1 demonstrated that the watershed scale was too comprehensive for preference elicitation and thus unrealistic for decision support through our DDST. Again, Study 1 functioned as a pilot study, and we used it as an opportunity to test out post-survey questions, so we did not ask researcher participants about single dam vs. multi-dam decision making. Stakeholder participants in Study 3 preferred (~78%) multi-dam decisions, where a slight majority (~54%) of student participants preferred single dam decisions in Study 2 (Figure 64).

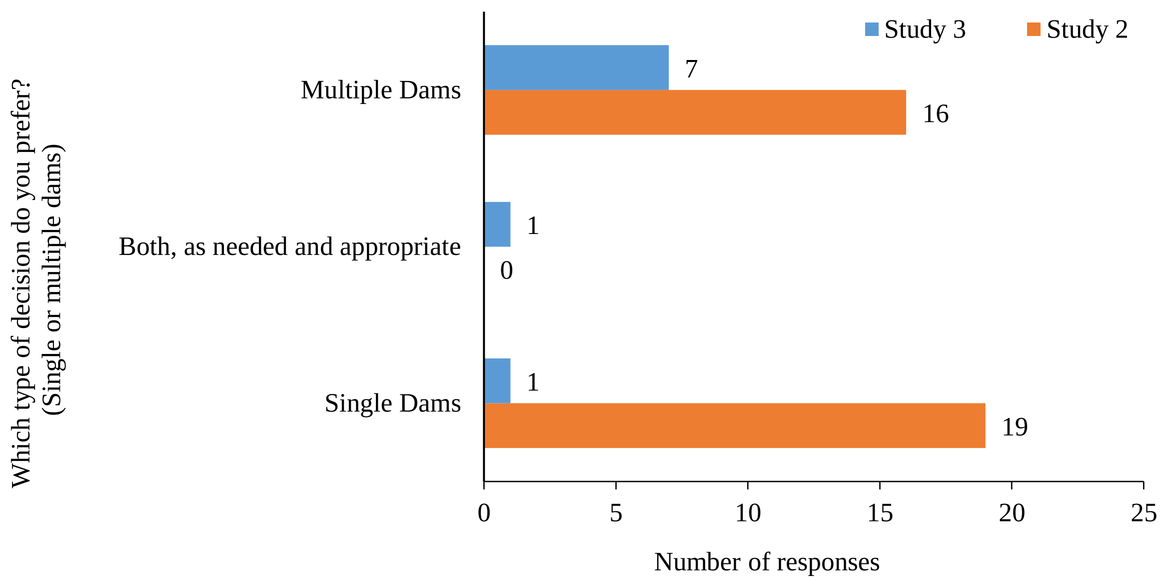

Figure 64. Responses to the post-survey question: Which type of decision did you prefer (single or multiple-dam)? Recall, the question was only asked in post-survey for Study 2 (n = 35) and Study 3 (n = 9).

Student participants seemed to value individual dam decisions because of the focus such a narrow decision space provided. Study 2 participants noted the following in their post-survey feedback:

> *"I think dams are complex, by the nature of adding more dams to your analysis it becomes difficult to decide on policy for a particular location."*-Student

"I prefer the single dam because of the fact that I can weigh the decisions better with just one dam in mind." -Student

"Each dam has its own unique persona and backstory, and it felt like if you couldn't just focus on one, it was detrimental to the rest. It's kinda[sic] like multi-tasking in a way." -Student

As a reminder, Study 2 participants did not have much background on hydropower dams before the workshop, so the slight majority preference for single dam decisions could also be reflective of students' more recently acquired understanding about dams and their impacts in rivers. I interpret the survey response as reflective of a shared need for some simplification in such a complex (and new) decision environment. However, there were proponents of multiple dam decision-making in Study 2, as well:

"The dams are not isolated from one another, a decision from one impacts another." -Student

"Upstream dam changes impact downstream dams and therefore must be considered as a system."-Student

"Multiple dam decision making is not necessarily easier but can help paint a broader picture of dams that are connected. If they are in the same watershed, changes to one may affect another."-Student

The concept of 'river as system' seems to have been communicated clearly to participants in Study 2, so while students may prefer single dam decision making on balance, they can recognize the importance of broadening one's perspective to consider upstream and downstream connectivity. Study 3 participants are familiar with 'river as system' thinking, as well as 'real world' dam decision making. They have either experienced the FERC process in action (it is designed around single project license review) or heard about/participated in the PRRP, which is considered a successful instance of multi-dam decision making in the Northeast region [17], [19]. Study 3 participants shared related, but different (from students) perspectives in the post-survey, when asked why they answered the way they did (about single vs. multi-dam decisions):

> *"You are ultimately reviewing a water system as a whole, looking at multiple dams then you can rank different items differently on a scaled review."*—Private sector company representative
>
> *"Multiple dams allow you to look at the watershed not just the impact of one project, one location."*—Federal agency representative
>
> *"Decisions associated with many of the dams are related to decisions at other dams and need to be considered. For example, removal of a dam lower on a river may not seem to provide great benefits for sea run fish habitat, but is very important in the context of other upstream dams being removed or receiving improved fish passage. Together they may open up much more habitat, that would not be possible in the context of a single dam."*
> —Tribal nation representative 2

Participants in Study 3 highlighted the need for a system/scaled approach to decision-making, even suggesting that single dam decision making is myopic for some fundamentally network-dependent decision criteria (e.g., sea-run fish habitat area). In general, comments seem to suggest that consideration of upstream and downstream factors is necessary and since the DDST facilitates that, I interpret this as another indication of the tool's potential use in capacity building.

The post-survey also included specific evaluation questions about model transparency and salience, the usefulness of workshop decision outcomes (e.g., top-ranked decision alternatives), and whether they would use a similar model in their decision-making process (Figure 44, Figure 51, Figure 62). In general, across the 3 studies, the positive responses (mean Likert rating 3.5 or higher) came from questions about the overall workshop experience, group negotiation activity, and model development. Importantly, participants in Studies 2 and 3 seemed to feel a connection to the model development process (i.e., that they actively participated in model construction). The negative responses (again, in general for the 3 studies) came from evaluation questions assessing the model as useful for participants' own decision making, the (un)realistic nature of the decision outcome, and the decision model breakdown (i.e., decision criteria).

5.3.4.1. Two-Dimensional Evaluation

To maintain consistency with Chapter 4, I evaluate embedded studies 1 – 3 based on the MCDA model and participatory processes used (Table 37) in these studies. I utilize the same two-dimensional evaluation scheme: Model Complexity and Depth of Engagement (refer to Chapter 4 or section 5.2.5. for a brief description of the rating scales). In general, I rate Depth of Engagement high for the participatory process, because the workshops were designed to engage groups of participants in deliberation over shared preferences. The actual rating depended on whether there was true consensus-building work (which would receive a 5) or another, less consensus-focused negotiation strategy like majority-rules voting, which would receive a 4 if coupled with group discussion (see Ch. 4 for an in-depth explanation of the differences in rating). In Studies 1 and 2, we left the group deliberation process open-ended, allowing groups at each workshop to select their strategies for identifying shared preference values. Studies 1 and 2 both rate at 4 for Depth of Engagement, because the deliberation process turned into a vote-based majority rule selection, rather than a discussion or negotiation leading to compromise or consensus. Study 1 groups did not refer to individual responses at all, preferring to begin anew in finding shared preference values. Study 2 groups referenced the group average, which was facilitated using the Excel data collection spreadsheets. By comparison, the group deliberation in Study 3 was more structured, with consensus identified as a clear goal from the outset. The facilitator asked DMs to discuss each decision criterion in turn, allowing the conversation to flow and asking probing questions as needed. The facilitator periodically checked in with the group about shared preference ratings if discussion stalled or veered too far off track. This structure and facilitation deepened the engagement of some DMs, who were specifically called on to share their thoughts. Process commitments made in the beginning of the workshop allowed the facilitator to rein in DM voices overpowering others. The deliberation became a true negotiation as one DM from a state agency asked for a justification for consensus as opposed to compromise. The state agency DM recommended borrowing 'points' from one decision alternative to allocate toward another in the interest of reaching a compromise. This suggestion encouraged other participants to carefully consider the *most important* shared outcome and reallocate their preference points as a group to achieve that desired outcome. This process actually helped to demonstrate how preferences shaped the outcome, because even though preference 'points' were reallocated from other criteria, the main thing was making sure that individuals were comfortable with the representation of shared preferences and the resulting outcome/recommendation. Not only did DMs participate in a true negotiation process toward a consensus-based outcome, but also they shaped the participatory process by requesting to shift consideration toward a compromise outcome and then worked together to 'game the system' toward the desired outcome. For this reason, Study 3 rates at 5 in the Depth of Engagement dimension.

Table 37. Study comparison

Study	Year	MCDA Model	Software	Scope	2-Dimensional Classification	
					Model Complexity	Depth of Engagement
1	Jun-18	AHP +MOGA	Excel	Penobscot Watershed	5	4
2	Mar-19	WS + MOGA	R/Shiny + Google Sheet	West Enfield, Medway, Ripogenus	5	4
3	Oct-19	WS	R/Shiny	West Enfield, Medway, Penobscot Mills Project (5 dams), Ripogenus	2	5

Studies 1 and 2 both rate at 5 for Model Complexity, because of the link between AHP and MOGA, and because they found the model to be confusing, or like a 'black box' (i.e., not at all transparent). Participants could not have run the MOGA model themselves, which is a defining characteristic of the 5 rating on Model Complexity. Study 3 rates at 2 for Model Complexity, because of the challenges participants noted in trying to understand the decision criteria, which in turn led to some confusion in linking the preferences with model outcomes. The arithmetic required for the WS MCDA, as well as the DDST 3 (unlike DDST 1 and, to an extent, DDST 2 because the data were external to the model), was not something that required researcher support to understand. It was the specifics of decision criteria definitions (especially the mathematical ones) that seemed to challenge people in each of the studies. In Studies 1 - 3, we provided participants with instructional materials before the workshop, so they had a chance to individually digest the criteria before rating them. In Study 3, one participant from an NGO was adamant that the criteria estimates were not something that the general public could understand. We did originally rely on participants to understand and interpret the criteria themselves (e.g., Studies 1 and 2), but in Study 3 we adapted to the need to explain them to the group, based on the number of questions we received in the introductory presentation. We opened the door to an extended question and answer session about decision criteria and alternatives in Study 3 because we walked participants through the decision criteria definitions one at a time. Despite the time allocated to discussing decision criteria definitions, participants expressed reservations about decision criteria and normalization procedures. The DDST 3 is thus rated 2 for Model Complexity, indicating an opportunity for further improvements in transparency and clarity. Study 3 provided new information to help us understand the user experience and refine the DDST further. Presently, the research team is finalizing the DDST (version 4) for public release.

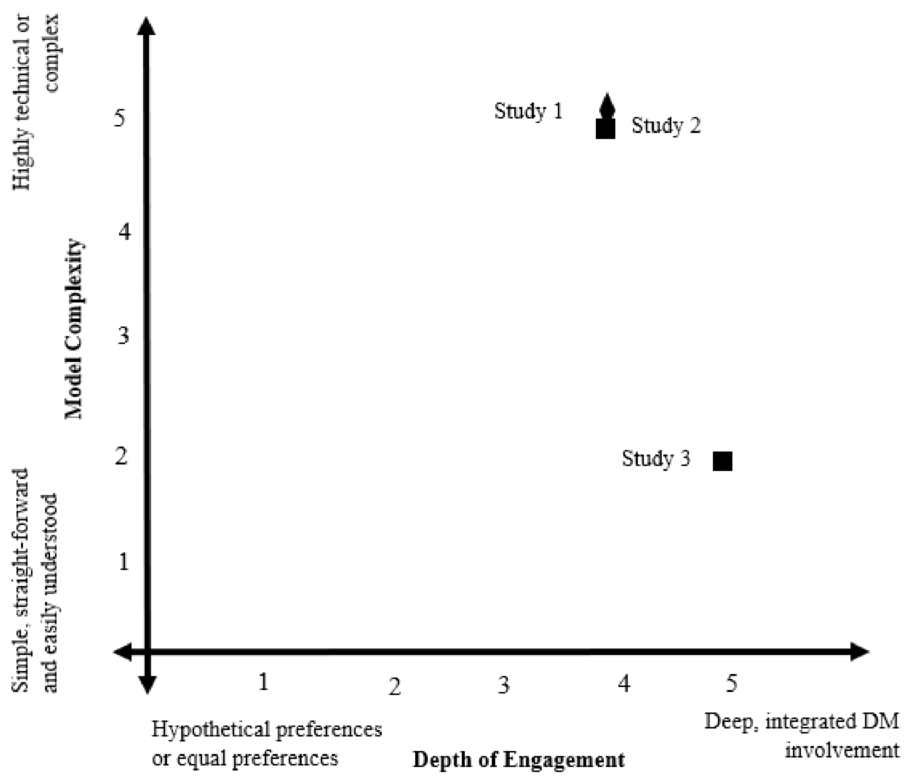

Figure 65. Study identification using a 2-dimensional rating used in Ch. 4, originally inspired by Marttunen et al. *[171]*.

5.4. Conclusion and Recommendations

In FERC's hydropower relicensing process, a public hearing is a required component because rivers are public waterways and public participation is a way to inform a relicensing decision (even if public comments contradict hydropower licensee narratives about dam operations). However, calls for public participation raise important questions over equity, extent, and ultimate impact of engagement (i.e., who, when, and level of influence stakeholders have on the final decision) [75], [215]. In FERC relicensing, where FERC considers licensees primary stakeholders, licensees have both the incentive and capacity to participate (they have a stake in the process outcome, that may impact their revenue from hydropower generation). Licensees may have the resources to dedicate a team to coordinating relicense applications, hire consultants to perform relevant environmental impact studies, or retain lawyers to advise them in legal matters relating to the dam. Licensees may also have immediate access to project information (costs, cash flows, environmental impacts) and historical site records that other actors do not. The intimacy of licensees with the dam site and hydropower operations gives them more influence than other actors to either effect change or maintain the status quo, unless legal tools (i.e., Endangered Species Act, Water Quality Act, certain municipal ordinances) are brought to bear on the license requirements or participants have greater access to information and enhanced capacity to participate in a way that is impactful to the relicensing process.

The DDST is designed to address *information access* and *participation capacity* by supporting participants in crossing those particular dam decision boundaries. I have shown that the DDST and workshop process provide users with access to scientific information including not only access to site-specific data (Dam Data Tables, Appendix K, sections 2.4 and 3.5) but also a means of reflecting on one's preferences for specific decision criteria. The DDST highlights different decision criteria and alternatives relevant to FERC hydropower dam relicensing. It changed over time to include Dam Factsheets, including a history of ownership and a list of potential stakeholders (Appendix K, section 2.3.) to aid the user in identifying preference ratings (which can be entered using slider bars in an intuitive UI), and now includes an interactive map that reveals key site characteristics (e.g., power capacity) when the user hovers the mouse over the site marker. DDST 1 did not include data in the UI, which was designed around pure preference elicitation, and garnered pushback from researcher participants about the lack of scientific information. DDST 2 included data, but not enough to help student participants feel as though they were informed enough to input preference ratings for decision criteria with any confidence. DDST 1 and DDST 2 separated the UI from the MOGA-MCDA calculation, lending to participant perceptions of the tool as a 'black box'. The MOGA model in DDST 1 and DDST 2 muddied participant understanding about how the MCDA calculation worked and contributed to participant perceptions of the tool as a 'black box'. Finally, in DDST 3, we let go of the MOGA, moved the MCDA calculation (including data tables at each step of the process) to the forefront of the UI to help support the user in understanding how the model went from preference ratings and criteria data to normalized criteria data and weighted normalized criteria data before ranking the decision alternatives and suggesting a recommendation.

I have also shown that the DDST reduces participatory boundaries (i.e., enhancing stakeholders' capacity to participate in dam decision making) through its design. The DDST: 1) is designed around a set of dams that are coming up for relicensing in the next 10 years, where motivated individuals or groups may use the DDST in planning or to facilitate early-stage conversations about the dams' futures; 2) provides a structured, interactive space for the user to get to know their preferences for decision criteria and explore the impacts of those preferences on the DDST-recommendation (i.e., the ranked MCDA scores); and 3) handles both individual and group preferences, providing support for users working through their priorities for the dam. The group preference aspect, or the ability of the tool to accommodate group participation, is where I see the capacity boundary being dissolved. In all 3 studies, participants reported learning from the group negotiation activity. Participant quotations from the post-surveys suggest that the exposure to other participants' priorities was a key part of this process. Study 2 post-survey responses indicate that repeated uses of the tool (i.e., both individually and with a group) may help to broaden individual perspectives about the decision problem. Study 3 post-survey responses suggest that the tool's design (e.g., incorporating multiple dams) may support multi-dam thinking and planning, if not for the specific relicensing process, then as a way to strategically "open up" discussions about decision criteria by sharing information early on in discussions about the future of a dam. The federal agency representative's perception that the tool could head off conflict if used to support early conversations about relicensing is the most promising piece of evidence supporting my claim of the DDST's potential role in reducing participatory boundaries.

Based on the post-survey evaluation questions, I assess that user-friendliness and decision context are both moving targets for DDST development. During the model development process, we made considerable tradeoffs in Model Complexity to enhance the participatory experience. User-friendliness is something that we considered seriously throughout DDST development but based on our tests with 3 very different user groups, *who* the user is matters to the evaluation of the user-friendliness goal. For instance, some students wanted less explanation/instruction text in the UI while others wanted more. While the research team attempted to find a synergistic solution to meet user needs for instruction in DDST 3, there are still some areas where additional explanation or clarity would improve UX. The fact that the decision criteria and alternatives were still widely regarded as non-salient in DDST 3 is something that prevents me from classifying the model as simple and straightforward on the Model Complexity spectrum. There are still some improvements to be made to the tool before it can be called user-friendly. Similarly, the adage "every dam is different" (which became a refrain during the stakeholder interview process) and the perception that every dam site is truly unique impacts the development of a representative model. Because every dam is different and accordingly every FERC relicensing process is different (not only due to site characteristics but also due to *who* participates and *when*), the perception amongst stakeholders seems to be that there is no way of anticipating every criterion that might be important for a particular dam. Our research team developed a set of possible decision criteria and alternatives that we identified as relevant based on stakeholder interviews, literature review, and FERC license orders. We tailored the DDST to the local context and designed the decision scenario around a set of dams coming up for relicensing in the next 10 years in Maine's Penobscot River.

Overall, the model development process was designed as an evolution, and more closely resembles UX research, with the final test with actual end-users (stakeholders, DMs), than typical pilot testing protocols for survey development. The reason for this methodological choice was because the final result was not a survey, but rather a tool whose usefulness hinges upon UX/UI. The DDST was designed to be used directly by people interested in participating in dam decision making. I have been asked if this type of process, where potential end-users are involved in testing, could lead to a self-fulfilling outcome where users contribute to the design of a tool that results in the recommendations they are looking for. First, stakeholder or DM perspectives are a form of evidence (for discussion about different forms of evidence see [71], [72]) that we have intentionally included in the design of this research. Because having a useful, user-friendly, and clear (if not completely transparent) DDST is our goal, the integration of end-user feedback is a deeply integral part of that process. To develop a DDST without end-user feedback would be to discount the perspectives of the boots-on-the-ground experts and to ignore the researcher's responsibility to participants to engage them meaningfully in the research (i.e., as more than a data source). Few et al. [75] remind us that participation is a promise to be honored in the engagement exercise; it might be called something else if participation is not the real intent. So, viewed from this perspective, a self-fulfilling outcome is (to some extent) the point. Second, there is power in a tool designed to allow the user to 'play' with different simulated preferences (i.e., equal weights, 'licensee' preferences, or 'fish-focused' non-profit preferences) to cultivate an understanding about what others' priorities are, and what their DDST-recommended outcome might be. The data prevent the MCDA from generating results that are chiefly reflective of preferences (i.e., site-specific data are still a part of the calculation), so the self-fulfillment is tempered by the actual mechanics of the MCDA. So, while the user can guess as to what the outcome could look like and could certainly participate strategically in a group negotiation setting (and this is true in real-world negotiations as well), the outcome is still data informed. And, there is much to be gained from 'playing around' with different simulated preferences, including cultivating some insight into others' priorities.

It was important to me to see firsthand the potential for stakeholder fatigue when using AHP, a critique in the literature that seems not to deter researchers from attempting to use it in a participatory setting. Wrestling with the early AHP model provided additional learning opportunities for me as a researcher as well. I tackled functionality in Excel because it is widely used, and I found no open-access or open-source AHP DDST that would suit our specific needs (see Ch. 4). I was drawn to AHP early on because its hierarchical problem characterization and thorough, built-in approach to preference elicitation seemed to outweigh the possible drawback of participant fatigue (see Ch. 4 for a discussion of this attribute of the AHP). This study prompted further evaluation of MCDA methods, as well as an exploration of other platforms for modeling, which eventually brought us to R Shiny.

There are limitations to this work, the most significant of which involves additional considerations for decision support into the FERC relicensing process. Though the DDST includes criteria for indigenous cultural traditions and lifeways, as well as sea-run fish habitat area, these two criteria also have legal requirements in the FERC process. Riparian sites with cultural importance restrict development. Hydropower projects on rivers with active sea-run fish populations (especially where sea-run species are endangered, e.g., Atlantic salmon) must meet requirements for fish passage, typically through state-of-the-art facilities (e.g., fish lift). Other federal laws impact FERC proceedings, too (e.g., Federal Power Act, National Environmental Protection Act, Endangered Species Act, Water Quality Act, etc.).

It seems that Antunes et al.'s 'analysis challenge' (where results interpretation is dependent on the participatory process, i.e., who is involved [91]) is a problem in the FERC process, if FERC's history indeed indicates a licensee-oriented predisposition (i.e., use of discretionary power benefitting the licensee) as Kosnik suggests [66], [213]. The FERC relicensing process solicits public participation, but participation may lack influence or power, especially without access to information or capacity to participate in an impactful way. In other words, the quality of participation matters to the final management decision outcome. Also, some decision alternatives may be more likely than others. While FERC approves the decision alternative, the licensee ultimately defines the set. There are unique circumstances, where the licensee has worked with stakeholders or DM agencies to come up with a settlement agreement to be approved by FERC, as in the PRRP [19], or where the DM agencies use legislation (e.g., the Endangered Species Act) to require the licensee to comply with another decision alternative, but by and large, the licensee has considerable power in the situation. And, although FERC is legally charged to consider environmental impacts as well as power production under the National Environmental Policy Act (1969) and judicially mandated by the Supreme Court to address every hydropower dam relicense application as a complete re-evaluation (see Yakima Indian Nation v. The Federal Energy Regulatory Commission, 1984), Kosnik's research suggests that FERC exhibits discretionary flexibility in its decision making [66]. While we include dam removal as a possible decision alternative in our DDST, the historical likelihood of FERC outright denying a license is vanishingly low [66]. Decisions involving the removal of hydropower dams are more likely to be negotiated directly with the dam owner in a settlement, before embarking on relicensing with FERC, as in the PRRP [17], [19]. I feel that settlement negotiation processes present real opportunities to use our DDST to support impactful participation. While not a formal part of the FERC process, settlements can certainly impact FERC proceedings.

One key finding from Study 3 was that, as-is, the DDST has potential to set the stage for conversations about relicensing before the process officially gets under way because it can help people to focus on existing data and shape the discussion around what is known about the dam and its operation. If used in an anticipatory manner (i.e., before the licensee sends the Notice of Intent and Pre-Application to FERC), and with enough stakeholders, the DDST and workshop process might be adapted to accommodate different site-specific decision criteria and alternatives as appropriate to meaningfully support hydropower dam conversations. Future work could entail using the tool in a public process, where participants are encouraged to 'play' with the DDST prior to attendance and then, with a trained facilitator, use the DDST to help structure a negotiation about shared criteria preference values. There are towns and cities upstream and downstream of the Penobscot River's hydropower dams that could use the DDST in a public meeting setting to support planning for their municipality's participation (or non-participation) in FERC relicensing.

Participatory considerations and practical stakeholder needs drove our research team's decisions about model development and workshop planning. The purpose of designing a custom DDST is to enhance said information access and support participatory capacity-building, ultimately creating a useful form of decision support for stakeholders and other actors. As the DDST (version 4) is being finalized for public access, our DDST research team has an eye on supporting the public in making the most of the tool and using it to inform their participation in FERC relicensing or any dam decision making. The web app is free to use, open-sourced, and it will be hosted on the University of New Hampshire Data Discovery Center website (https://ddc.unh.edu/dams-mcda/). The code for the web app can be found on GitHub (https://github.com/dams-mcda), making it accessible for more advanced R users to download and modify the DDST to suit their needs. The Data Discovery Center website will also include basic instructions for how to download and modify the key features of the app (e.g., decision criteria, alternatives, dams) in R for users outside of the Penobscot River watershed. Future work might entail additional versioning of the DDST where (in a manner similar to what we attempted in DDST 2) a 'base' version is generic, focused on a single dam, and with user options to write in their own decision criteria and pre-load any data they may have (e.g., annual electricity generation), with Likert scale inputs for subjective criteria (e.g., aesthetics) or criteria for which there is little to no data available. The 'base' DDST would be something that could be used with any dam, anywhere. The site-specific data we use in DDST 3 would then act as example modules to show how the 'base' DDST could be tailored to a specific dam. While site specificity was called for in our development of the DDST, a more generic 'base' version for users certainly would make the tool more flexible and applicable to multiple dam contexts.

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APPENDIX A: TURBINE TYPES, DESCRIPTION, APPLICATION

Table A1. Turbine Comparison

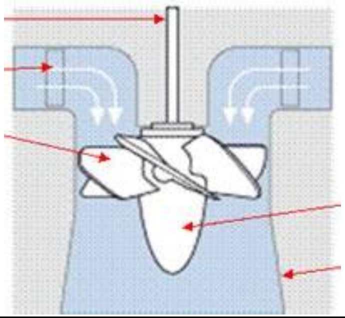
Picture	Turbine type	Category	Description	Head (ft)	Flow (cfs)	Citation
	Pelton	Impulse	Powered by jets of water discharged through one to several nozzles, hitting a runner with split buckets [100]. This type of turbine is only partially submerged and does not require draft tubes. Suitable at high head sites and lower flow rates, as in mountains [1], and can operate efficiently at flows less than designed [100].	66 - 1640 [100]	0 – 35 [100]	[236]
	Turgo	Impulse	A variation on the Pelton made by Gilkes (UK), the Turgo runner resembles a fan blade that is closed on the outer edges (rather than the split buckets of the Pelton). Suitable at medium heads, the Turgo is able to run at higher speeds than the Pelton, allowing it to be coupled with the generator [100]. Operates most efficiently in high heads but is acceptable in medium head ranges (much like the Pelton).	66 - 1640 [100]	0 – 35 [100]	[237]
	Kaplan	Reaction	The most common type of propeller-type turbine (others include Straflo, bulb, and tube) [100]. Water flow around runner blades produces a reaction force due to the airfoil action in a fully submerged chamber within the casing. Can be double-regulated using blades and wicket gates to adjust output [1]. Modifications of this style include the following configurations: Z, S, pit, vertical, and bulb [1].	10 - 26 [100]	106 - 706 [100]	[238]

Table A1. (Continued)

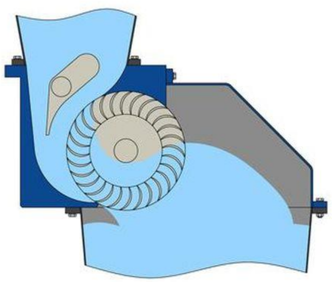
Picture	Turbine type	Category	Description	Head (ft)	Flow (cfs)	Citation
	Francis	Reaction/Impuse	The first modern turbine invention uses curbed impellor blades and can be configured vertically or horizontally. Not a pure reaction turbine; some force comes from impulse action (mixed radial/axial flow) [100].	13 - 328 [100]	18 - 141 [100]	[239]
	Cross-flow	Impulse	Also known as a Banki turbine. The rotor in a cross-flow turbine is drum-shaped and uses elongated section nozzle directed against a small portion of curved vanes along the cylindrical runner, where water passes a second time through the opposite side [100]. Suitable at medium to low heads.	3 – 200m [240]	<1 cms - ~15 cms* [240]	[240]
	Propeller	Reaction	Axial flow runner with three to six adjustable blades in which the water contacts all blades within a "snail shell" housing [100]. Kaplan, Straflo, and tube turbines are all variations of the general propellor design.	~10 - 26 [100]	~106 - 706 ([100]	[241]

Table A1. (Continued)

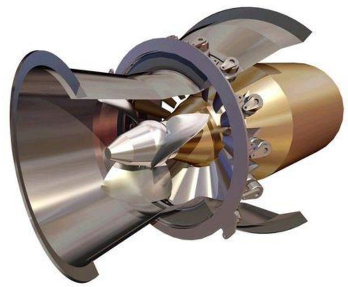
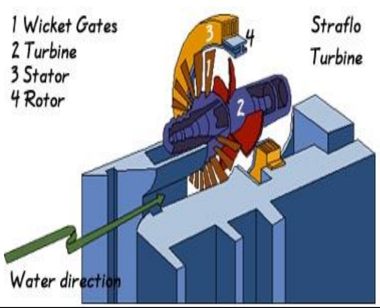
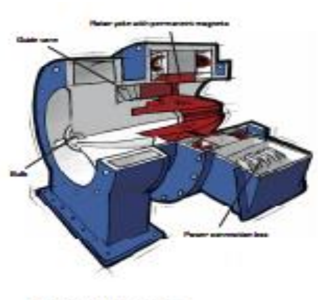
Picture	Turbine type	Category	Description	Head (ft)	Flow (cfs)	Citation
	Bulb turbine	Reaction	Propeller type turbine sealed in a unit directly in the water stream [54]. Rated for up to 80 MW [242].	2 – 1059 [242], [243]	No data	[244]
	Straflo	Reaction	“Straight flow” propeller type turbine [245] is similar to a bulb turbine, situated directly in the water stream. The generator is attached to the runner [246].	No data	10,594 [245]	[245]
	Turbinator	Reaction	Modified Straflo turbine	16 - 180 [13]	35 – 353 [247]	[247]

Table A1. (Continued)

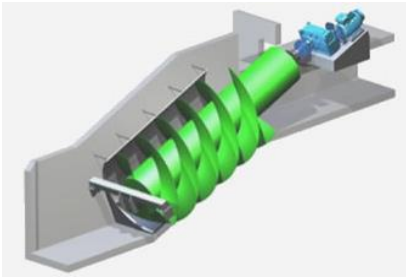
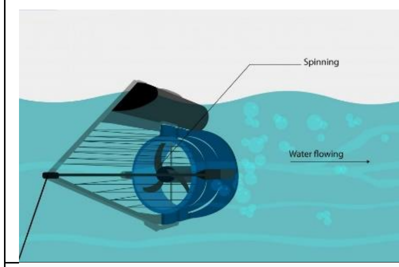
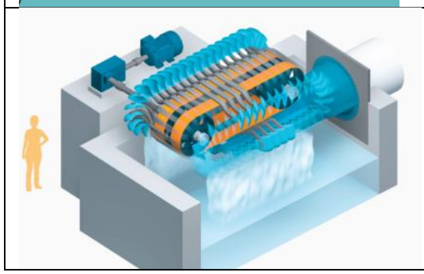
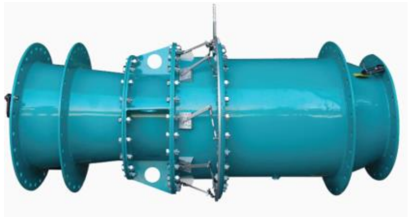
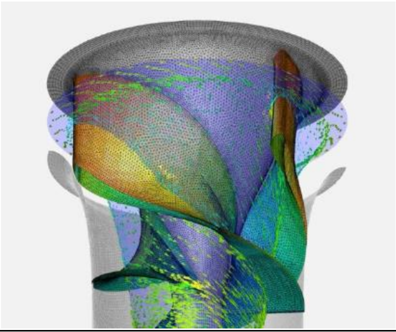
Picture	Turbine type	Category	Description	Head (ft)	Flow (cfs)	Citation
	Screw generator	Modified reaction	"Bespoke installation" diameter and size is determined by specific site [100]. Screw moves more slowly than most turbines; they extract potential energy from water falling downward through the threads of a tilted screw. Flow is controlled by sluice gates. Suited for SHP projects with low heads [1], [100].	6 – 33 [100]	3 – 353 [248]	[249]
	Kinetic/ free-flow	Reaction	Kinetic turbine uses the kinetic energy of free flowing stream to turb the propellor blades, and need not divert the natural flow of the river [100]. Structure gets installed on the bed of the river or canal; compact, modular. Expandable (actual turbine has three propellor blades) unit is positioned with the flow of the water. May be suitable for installation behind traditional hydropower plants, within canals/conduits, or as an off-grid solution [250].	0	Dependent on river flow	[250]
	Linear Pelton	Reaction	Open flow, cylindrical runners, vertical discharge, and no draft tube. Designed for high flows at low heads. Rated from 0.025 MW - 1 MW.	23 - 65 [251]	5 - 280 [251]	[114]

Table A1. (Continued)

Picture	Turbine type	Category	Description	Head (ft)	Flow (cfs)	Citation
	Restoration Hydro Turbine	Reaction	Allows for safe fish passage (curved runner blades), short draft tube, low risk for cavitation. Rated from 0.032 MW – 1.4 MW. Comes in 3 designs: radial open flume, axial pit, z-type.	6 – 33 [251]	4 – 880 [251]	[251]
	Alden	Modified reaction	Allows for the downstream passage of fish directly through the turbine, similar to an Archimedes Screw.	75 - 100 [252]	1000- 1800 [252]	[253]
	Turbulent	Modified reaction	Allows for the downstream passage of fish directly through the turbine [254]–[256], similar to the Alden 'fish friendly' turbine or the Archimedes Screw. Up to 15 kW power capacity for small communities [254].	5 – 16 [256]	27 – 205 [256]	[255]

APPENDIX B: NPV DATA

Table B1. Net Present Value Data from Application Studies

Author(s)	Location	Project Capacity (kW)	Discount Rate (%)	Electricity Price (2019 USD/kWh)	Project Lifetime (years)	NPV Estimate (2019 USD)	NPV/kW (2019 USD/kW)	Electricity (MWh/yr)
Kaldellis et al. [55]	Greece	10,000	10	0.15	20			38,400
Anagnstopoulos & Papantonis [38]	Greece	860	10	NS	20	(1,757,036)	(2,043)	2877
Anagnstopoulos & Papantonis [38]	Greece	8460	10	NS	20	9,815,748	1,160	28300
Anagnstopoulos & Papantonis [38]	Greece	8720	10	NS	20	9,393,383	1,077	29170
Anagnstopoulos & Papantonis [38]	Greece	5040	10	NS	20	13,414,292	2,662	26900
Anagnstopoulos & Papantonis [38]	Greece	3830	10	NS	20	12,637,142	3,300	12812
Forouzbakhsh et al. [53]	Iran	1750	10	NS	50	5,913,101	3,379	8440
Forouzbakhsh et al. [53]	Iran	1750	10	NS	50	5,186,634	2,964	7450
Forouzbakhsh et al. [53]	Iran	2500	10	NS	50	8,886,546	3,555	11230
Forouzbakhsh et al. [53]	Iran	2500	10	NS	50	7,822,188	3,129	10190
Forouzbakhsh et al. [53]	Iran	2500	10	NS	50	6,909,881	2,764	9230
Forouzbakhsh et al. [53]	Iran	2500	10	NS	50	6,183,414	2,473	8580
Forouzbakhsh et al. [53]	Iran	2500	10	NS	50	5,440,053	2,176	7810
Forouzbakhsh et al. [53]	Iran	2500	10	NS	50	4,477,062	1,791	6950
Forouzbakhsh et al. [53]	Iran	3750	10	NS	50	12,299,250	3,280	13770
Forouzbakhsh et al. [53]	Iran	3750	10	NS	50	9,849,537	2,627	11570

Table B1. (Continued)

Author(s)	Location	Project Capacity (kW)	Discount Rate (%)	Electricity Price (2019 USD/kWh)	Project Lifetime (years)	NPV Estimate (2019 USD)	NPV/kW (2019 USD/kW)	Electricity (MWh/yr)
Forouzbakhsh et al. [53]	Iran	3750	10%	NS	50	7,737,715	2,063	9830
Forouzbakhsh et al. [53]	Iran	3750	10%	NS	50	8,312,131	2,217	9470
Forouzbakhsh et al. [53]	Iran	5000	10%	NS	50	12,012,042	2,402	13790
Forouzbakhsh et al. [53].	Iran	5000	10%	NS	50	9,900,221	1,980	11530
Bockman et al. [37]	Norway	4500	NS	0.04	30	6,082,047	1,352	14703
Bockman et al. [37]	Norway	NS	NS	0.04	30	3,209,969		8358
Bockman et al. [37]	Norway	NS	NS	0.06	30	1,469,828		4930
Santolin et al. [32]	Italy	NS	5%	NS	15	NS	NS	NS
Santolin et al. [32]	Italy	NS	5%	NS	15	NS	NS	NS
Santolin et al. [32]	Italy	NS	5%	NS	15	NS	NS	NS
Sandt & Doyle [31]	North Carolina, U.S.	*85*	5%	*0.14*	30	*568,081*	*0.01*	*355*
Zema et al. [94]	Italy	107	NS	NS	25	1,136,851	10,655	538
Zema et al. [94]	Italy	101	NS	NS	25	1,161,732	11,502	509
Zema et al. [94]	Italy	313	NS	NS	25	2,594,204	8,293	1577
Cunha & Ferreira [49]	Portugal	1900	10%	NS	25	1,361,035	716	6124
Kusakana [50]	South Africa	4	NS	NS	25	58,612	15,424	13
Kusakana [50]	South Africa	6	NS	NS	25	82,373	14,710	22
Nair & Nithiyananthan [44]	Malaysia	506	10%	0.06	20	346,287	684	1638

Table B1. (Continued)

Author(s)	Location	Project Capacity (kW)	Discount Rate (%)	Electricity Price (2019 USD/kWh)	Project Lifetime (years)	NPV Estimate (2019 USD)	NPV/kW (2019 USD/kW)	Electricity (MWh/yr)
Nair & Nithiyananthan [44]	Malaysia	491	10%	0.06	20	246,080	501	1661
Nair & Nithiyananthan [44]	Malaysia	484	10%	0.06	20	365,477	755	1712
Nair & Nithiyananthan [44]	Malaysia	467	10%	0.06	20	311,250	666	1580
Akcay et al. [42]	Turkey	7500	NS	0.06	NS	(2,755,263)	(367)	67500
Akcay et al. [42]	Turkey	7500	NS	0.06	NS	58,859,492	7,848	90000
Akcay et al. [42]	Turkey	7500	NS	0.70	NS	196,930,153	26,257	112500
Alonso-Tristan et al. [52]	Spain	400	4.10%	NS	50	3,719,463	9,299	1479
Gagliano et al. [47]	Italy	77	8%	0.22	20	282,286	3,666	220
Adhikary et al. [48]	India	6000	NS	0.07	35	5,716,742	953	NS
Karamarkovic et al. [163]	Serbia	1475	5	0.01	10			185
Karamarkovic et al. [163]	Serbia	250	5	0.01	12	319,416.96	1,279.20	203.7
Karamarkovic et al. [163]	Serbia	250	5	0.01	12			203.7
Karamarkovic et al. [163]	Serbia	522	5	0.01	10			388.6
Karamarkovic et al. [163]	Serbia	1996	5	0.01	12	266,324	133	800.8

APPENDIX C: BCR DATA

Table C1. Benefit Cost Ratio Data from Application Studies

Author(s)	Location	Capacity (kW)	Annual Generation (MWh)	Capacity Factor (%)	Discount Rate (%)	BCR	IRR	Site Name
Anagnostopoulos & Papantonis [38]	Greece	860	2877	0.38	10	0.82		Sim1
Anagnostopoulos & Papantonis [38]	Greece	3840	28300	0.38	10	2.31		Sim2
Anagnostopoulos & Papantonis [38]	Greece	5040	29170	0.38	10	2.2		Sim3
Anagnostopoulos & Papantonis [38]	Greece	8460	26900	0.61	10	1.59		Sim4
Anagnostopoulos & Papantonis [38]	Greece	8720	12812	0.38	10	1.58		Sim5
Forouzbakhsh et al. [53]	Iran	3750	11570	0.35	6	5.11		Alternative10
Forouzbakhsh et al. [53]	Iran	3750	11570	0.35	8	3.60		Alternative10
Forouzbakhsh et al. [53]	Iran	3750	11570	0.35	10	2.67		Alternative10
Forouzbakhsh et al. [53]	Iran	3750	11570	0.35	12	2.08		Alternative10
Forouzbakhsh et al. [53]	Iran	3750	11570	0.35	14	1.68		Alternative10
Forouzbakhsh et al. [53]	Iran	3750	11570	0.35	16	1.40		Alternative10
Forouzbakhsh et al. [53]	Iran	3750	11570	0.35	18	1.20		Alternative10
Forouzbakhsh et al. [53]	Iran	3750	11570	0.35	20	1.04		Alternative10
USACE [9]	California, U.S.	2480	9350	0.43	4	1.29	6%	Hidden Dam
USACE [9]	Missouri, U.S.	2590	10500	0.14	4	1.22	6%	Clearwater Dam
USACE [9]	California, U.S.	2980	11258	0.43	4	1.68	10%	Buchanan Dam
USACE [9]	Ohio, U.S.	3090	22201	0.09	4	1.13	5%	Paint Creek Dam
USACE [9]	New Mexico, U.S.	3610	19781	0.63	4	2.42	15%	Santa Rosa Dam
USACE [9]	California, U.S.	4120	23101	0.64	4	2.21	13%	North Fork Dam

Table C1. (Continued)

Author(s)	Location	Capacity (kW)	Annual Generation (MWh)	Capacity Factor (%)	Discount Rate (%)	BCR	IRR	Site Name
USACE [9]	Arizona, U.S.	4160	11396	0.31	4	1.22	6%	Alamo Dam
USACE [9]	New York, U.S.	6160	20752	0.15	4	1.13	5%	Whitney Point Dam
USACE [9]	Pennsylvania, U.S.	6770	6026	0.1	4	1.16	5%	Tioga Dam
USACE [9]	Pennsylvania, U.S.	7370	11938	0.18	4	1.29	6%	Blue Marsh Dam
USACE [9]	Mississippi, U.S.	7700	34435	0.51	4	1.1	5%	Amory Dam
USACE [9]	Ohio, U.S.	8980	26406	0.34	4	1.32	9%	Bolivar Dam
USBR [10]	Utah, U.S.	444	2909	0.75	4	1.31	7%	Soldier Creek Dam
USBR [10]	Colorado, U.S.	484	2854	0.67	4	1.09	5%	Granby Dam
USBR [10]	South Dakota, U.S.	596	2725	0.52	4	1.01	5%	Pactola Dam
USBR [10]	Wyoming, U.S.	743	5508	0.85	4	1.16	6%	Pathfinder Dam
USBR [10]	California, U.S.	872	3819	0.50	4	1.06	5%	Prosser Creek Dam
USBR [10]	Colorado, U.S.	981	5648	0.66	4	1.17	6%	Twin Lakes Dam
USBR [10]	Washington, U.S.	1057	7400	0.80	4	1.58	9%	Easton Diversion Dam
USBR [10]	Wyoming, U.S.	1062	6337	0.68	4	1.03	5%	Willwood Diversion Dam
USBR [10]	Arizona, U.S.	1079	5325	0.56	4	1.05	5%	Imperial Dam
USBR [10]	Washington, U.S.	1362	10182	0.85	4	1.35	7%	Sunnyside Dam
USBR [10]	Colorado, U.S.	1435	9220	0.73	4	1.2	6%	Gunnison Diversion Dam
USBR [10]	Colorado, U.S.	1979	14246	0.82	4	1.45	8%	Grand Valley Diversion Dam
USBR [10]	Wyoming, U.S.	2067	13059	0.72	4	1.49	8%	Gray Reef Dam
USBR [10]	Colorado, U.S.	2224	11343	0.58	4	1.18	6%	South Canal "Site #3"
USBR [10]	Washington, U.S.	2276	11238	0.56	4	1.18	6%	Scootney Wasteway
USBR [10]	Montana, U.S.	2426	17430	0.82	4	1.74	10%	Huntley Diversion Dam
USBR [10]	Colorado, U.S.	2465	12576	0.58	4	1.24	6%	South Canal "Site #1"

Table C1. (Continued)

Author(s)	Location	Capacity (kW)	Annual Generation (MWh)	Capacity Factor (%)	Discount Rate (%)	BCR	IRR	Site Name
USBR [10]	Colorado, U.S.	2543	12488	0.56	4	1.05	5%	Taylor Park Dam
USBR [10]	Montana, U.S.	2626	9608	0.42	4	1.29	7%	Helena Valley Pumping Plant
USBR [10]	New Mexico, U.S.	2701	8874	0.38	4	1	5%	Heron Dam
USBR [10]	Colorado, U.S.	2862	15419	0.62	4	1.77	10%	M&D Canal-Shavano Falls
USBR [10]	Utah, U.S.	3043	13168	0.49	4	1.15	6%	Starvation Dam
USBR [10]	Colorado, U.S.	3046	15536	0.58	4	1.35	7%	South Canal "site #4"
USBR [10]	Montana, U.S.	3078	13689	0.51	4	1.42	8%	Clark Canyon Dam
USBR [10]	New Mexico, U.S.	3260	15095	0.53	4	1.36	7%	Caballo Dam
USBR [10]	Oregon, U.S.	3293	18282	0.63	4	1.79	10%	Arther R. Bowman Dam
USBR [10]	Colorado, U.S.	3366	14040	0.48	4	1.27	7%	Ridgeway Dam
USBR [10]	Colorado, U.S.	3830	19057	0.57	4	1.45	8%	Gunnison Tunnel
USBR [10]	Arizona, U.S.	7529	36880	0.56	4	2.25	12%	Bartlett Dam
USBR [10]	Utah, U.S.	8114	22920	0.32	4	1.57	9%	Spanish Forth Flow Control Structure
USBR [10]	Montana, U.S.	8521	30774	0.41	4	1.23	6%	Gibson Dam
USBR [10]	Montana, U.S.	9203	68261	0.85	4	2.86	16%	Yellowtail Afterbay Dam
Zhang et al. [13]	Oregon, U.S.	15	59	0.45	6	0.38		Watson Reservoir
Zhang et al. [13]	Oregon, U.S.	16	75	0.54	6	1.06	9%	Allen Creek
Zhang et al. [13]	Oregon, U.S.	20	94	0.54	6	1.05	9%	Bear Creek
Zhang et al. [13]	Oregon, U.S.	29	118	0.46	6	0.09		Layton #2 Reservoir
Zhang et al. [13]	Oregon, U.S.	31	160	0.59	6	0.23		Gilchrist Log Pond
Zhang et al. [13]	Oregon, U.S.	33	128	0.44	6	0.51		Bonnie View Dam
Zhang et al. [13]	Oregon, U.S.	39	289	0.85	6	0.29		Fehrenbacker #2
Zhang et al. [13]	Oregon, U.S.	39	179	0.52	6	1.22	12%	Merwin Reservoir #2
Zhang et al. [13]	Oregon, U.S.	75	305	0.46	6	0.86	4%	58-9 Lateral

Table C1. (Continued)

Author(s)	Location	Capacity (kW)	Annual Generation (MWh)	Capacity Factor (%)	Discount Rate (%)	BCR	IRR	Site Name
Zhang et al. [13]	Oregon, U.S.	137	560	0.47	6	0.96	5%	58-11 Lateral
Zhang et al. [13]	Oregon, U.S.	187	942	0.58	6	0.28		McKenzie Reservoir
Zhang et al. [13]	Oregon, U.S.	200	657	0.38	6	0.52		Crescent Lake Dam
Zhang et al. [13]	Oregon, U.S.	337	2037	0.69	6	0.81	<0%	Crane Prairie
Zhang et al. [13]	Oregon, U.S.	352	1461	0.47	6	0.57		Young Ave
Zhang et al. [13]	Oregon, U.S.	366	2992	0.93	6	1.74	<0%	Ochoco Dam
Zhang et al. [13]	Oregon, U.S.	399	1672	0.48	6	0.58		10-Barr Road
Zhang et al. [13]	Oregon, U.S.	444	1751	0.45	6	0.46		Smith Rock Drop
Zhang et al. [13]	Oregon, U.S.	445	1854	0.48	6	0.69	0%	NC-2 Fall
Zhang et al. [13]	Oregon, U.S.	516	2174	0.48	6	0.45		Yew Ave
Zhang et al. [13]	Oregon, U.S.	609	3070	0.58	6	0.39		Ward Road
Zhang et al. [13]	Oregon, U.S.	850	4071	0.55	6	0.36		Shumway Road
Zhang et al. [13]	Oregon, U.S.	861	3461	0.46	6	0.31		Brasada Siphon
Zhang et al. [13]	Oregon, U.S.	1015	4004	0.45	6	0.65		Brinson Blvd
Zhang et al. [13]	Oregon, U.S.	1135	5145	0.52	6	0.72	2%	North Canal Diversion Dam
Zhang et al. [13]	Oregon, U.S.	1396	6690	0.55	6	0.48		Dodds Road
Zhang et al. [13]	Oregon, U.S.	1730	8078	0.53	6	0.90	5%	Haystack Canal
Zhang et al. [13]	Oregon, U.S.	2700	12556	0.53	6	1.03	6%	Mile-45
Zhang et al. [13]	Oregon, U.S.	5959	19587	0.38	6	1.47	11%	Bowman Dam
Zhang et al. [13]	Oregon, U.S.	7118	29010	0.47	6	1.44	10%	Wickiup Dam

APPENDIX D: LCOE DATA

Table D1. Levelized Cost of Energy Comparison

Author(s)	Capacity (kW)	Capacity Factor (%)	Discount Rate (%)	Project Lifetime (years)	LCOE Estimate ($2019/MWh)	Site Name
IRENA [103]	NS	*49*	*7*	NS	*159.5*	NS
IRENA [103]	NS	NS	*7*	NS	*33.0*	NS
Zhang et al. [12]	6000	38	NS	NS	68.4	NS
Zhang et al. [12]	3000	52	NS	NS	50.6	NS
Zhang et al. [12]	3700	54	NS	NS	47.7	NS
Zhang et al. [12]	3000	36	NS	NS	48.7	NS
Zhang et al. [12]	5000	50	NS	NS	173.6	NS
Zhang et al. [12]	5000	50	NS	NS	148.7	NS
Zhang et al. [12]	6400	22	NS	NS	107.0	NS
Zhang et al. [12]	10300	61	NS	NS	49.0	NS
Motwani et al. [51]	3	60	12	10	17.9	NS
Motwani et al. [51]	3	80	12	25	112.7	NS
O'Connor et al. [11]	*43930*	NS	6	NS	*132.5*	NS
O'Connor et al. [11]	*13070*	NS	NS	NS	NS	NS
O'Connor et al. [11]	*1730*	NS	NS	NS	NS	NS
O'Connor et al. [11]	*12270*	NS	NS	NS	NS	NS
Zhang et al. [13]	15	0.45	6	NS	238.8	Watson Reservoir
Zhang et al. [13]	16	0.54	6	NS	84.8	Allen Creek
Zhang et al. [13]	20	0.54	6	NS	85.4	Bear Creek
Zhang et al. [13]	29	0.46	6	NS	1007.8	Layton #2 Reservoir
Zhang et al. [13]	31	0.59	6	NS	426.5	Gilchrist Log Pond
Zhang et al. [13]	33	0.44	6	NS	174.2	Bonnie View Dam
Zhang et al. [13]	39	0.85	6	NS	441.2	Fehrenbacker #2
Zhang et al. [13]	39	0.52	6	NS	73.5	Merwin Reservoir #2
Zhang et al. [13]	75	0.46	6	NS	94.5	58-9 Lateral
Zhang et al. [13]	137	0.47	6	NS	85.2	58-11 Lateral
Zhang et al. [13]	187	0.58	6	NS	296.6	McKenzie Reservoir
Zhang et al. [13]	200	0.38	6	NS	160.4	Crescent Lake Dam
Zhang et al. [13]	337	0.69	6	NS	117.5	Crane Prairie

Table D1. (Continued)

Author(s)	Capacity (kW)	Capacity Factor (%)	Discount Rate (%)	Project Lifetime (years)	LCOE Estimate ($2019/MWh)	Site Name
Zhang et al. [13]	352	0.47	6	NS	175.9	Young Ave
Zhang et al. [13]	366	0.93	6	NS	76.6	Ochoco Dam
Zhang et al. [13]	399	0.48	6	NS	140.0	10-Barr Road
Zhang et al. [13]	444	0.45	6	NS	191.0	Smith Rock Drop
Zhang et al. [13]	445	0.48	6	NS	116.5	NC-2 Fall
Zhang et al. [13]	516	0.48	6	NS	182.2	Yew Ave
Zhang et al. [13]	609	0.58	6	NS	208.7	Ward Road
Zhang et al. [13]	850	0.55	6	NS	226.1	Shumway Road
Zhang et al. [13]	861	0.46	6	NS	262.7	Brasada Siphon
Zhang et al. [13]	1015	0.45	6	NS	122.4	Brinson Blvd
Zhang et al. [13]	1135	0.52	6	NS	81.1	North Canal Diversion Dam
Zhang et al. [13]	1396	0.55	6	NS	169.1	Dodds Road
Zhang et al. [13]	1730	0.53	6	NS	66.5	Haystack Canal
Zhang et al. [13]	2700	0.53	6	NS	77.5	Mile-45
Zhang et al. [13]	5959	0.38	6	NS	33.8	Bowman Dam
Zhang et al. [13]	7118	0.47	6	NS	55.9	Wickiup Dam
Balkhair & Rahman [43]	291	0.75	NS	25	32	Upper Swat Canal (main-1)
Balkhair & Rahman [43]	305	0.75	NS	25	32	Upper Swat Canal (main-2)
Balkhair & Rahman [43]	264	0.75	NS	25	32	Upper Swat Canal (main-3)
Balkhair & Rahman [43]	359	0.75	NS	25	32	Upper Swat Canal (main-4)
Balkhair & Rahman [43]	222	0.75	NS	25	32	Upper Swat Canal (main-5)
Balkhair & Rahman [43]	254	0.75	NS	25	32	Upper Swat Canal (main-6)
Balkhair & Rahman [43]	279	0.75	NS	25	32	Upper Swat Canal (main-7)
Balkhair & Rahman [43]	239	0.75	NS	25	32	Upper Swat Canal (main-8)
Balkhair & Rahman [43]	561	0.75	NS	25	32	Upper Swat Canal (main-9)
Balkhair & Rahman [43]	211	0.75	NS	25	32	Upper Swat Canal (main-10)
Balkhair & Rahman [43]	217	0.75	NS	25	32	Upper Swat Canal (Machai branch-1)
Balkhair & Rahman [43]	201	0.75	NS	25	32	Upper Swat Canal (Machai branch-2)
Balkhair & Rahman [43]	276	0.75	NS	25	32	Upper Swat Canal (Machai branch-3)
Balkhair & Rahman [43]	379	0.75	NS	25	32	Upper Swat Canal (Machai branch-4)
Balkhair & Rahman [43]	258	0.75	NS	25	32	Upper Swat Canal (Machai branch-5)

Table D1. (Continued)

Author(s)	Capacity (kW)	Capacity Factor (%)	Discount Rate (%)	Project Lifetime (years)	LCOE Estimate ($2019/MWh)	Site Name
Balkhair & Rahman [43]	224	0.75	NS	25	32	Upper Swat Canal (Machai branch-6)
Balkhair & Rahman [43]	275	0.75	NS	25	32	Upper Swat Canal (Machai branch-7)
Balkhair & Rahman [43]	241	0.75	NS	25	32	Upper Swat Canal (Machai branch-8)
Balkhair & Rahman [43]	201	0.75	NS	25	32	Upper Swat Canal (Machai branch-9)
Balkhair & Rahman [43]	179	0.75	NS	25	32	Upper Swat Canal (Machai branch-10)
Park et al. [54]	101	0.35	6.75	25	266	Very low head project 1
Park et al. [54]	1478	0.35	6.75	25	85	Very low head project 2
Park et al. [54]	1002	0.35	6.75	25	76	Very low head project 3
Park et al. [54]	100	0.35	6.75	25	113	Low head project 1
Park et al. [54]	1068	0.35	6.75	25	53	Low head project 2
Park et al. [54]	1003	0.35	6.75	25	47	Low head project 3
Park et al. [54]	102	0.35	6.75	25	133	Medium head project 1
Park et al. [54]	1066	0.35	6.75	25	48	Medium head project 2
Park et al. [54]	1004	0.35	6.75	25	44	Medium head project 3
Park et al. [54]	100	0.35	6.75	25	80	High head project 1
Park et al. [54]	308	0.35	6.75	25	56	High head project 2
Park et al. [54]	1004	0.35	6.75	25	46	High head project 3
Alonso-Tristan et al. [52]	400	0.42	4.10%	50	80	Asturwatt
Adhikary et al. [48]	6000	NS	NS	35	46	Bihar
Carapellucci et al. [45]	NS	NS	5	30	36 -323	Aterno-Pescara
Carapellucci et al. [45]	NS	NS	5	30	>120	Sangro
Carapellucci et al. [45]	NS	NS	5	30	60-251	Vomano
Carapellucci et al. [45]	NS	NS	5	30	>120	Saline
Carapellucci et al. [45]	NS	NS	5	30	>120	Tordino
Carapellucci et al. [45]	NS	NS	5	30	48 - 515	Liri-Garigliano
Carapellucci et al. [45]	NS	NS	5	30	>120	Sinello
Carapellucci et al. [45]	NS	NS	5	30	>120	Foro

APPENDIX E: COST EQUATIONS

Table E1. Cost Equation Comparison

Author	Cost Type	Location	Infr. Category	Head Range (m)	Capacity Range (kW)	Estimated value of *a*	Estimated value of b	Estimated value of c	Currency	Cost Model Estimation
Hall et al. [36]	Construction	U.S.	NSD	NS	NS	3300000	0.9	NS	USD	$C=aP^b$
Hall et al. [36]	Construction	U.S.	NPD	NS	NS	2200000	0.81	NS	USD	$C=aP^b$
Hall et al. [36]	Construction	U.S.	PD	NS	NS	1400000	0.81	NS	USD	$C=aP^b$
Hall et al. [36]	Licensing	U.S.	NSD	NS	NS	610000	0.70	NS	USD	$C=aP^b$
Hall et al. [36]	Licensing	U.S.	NPD	NS	NS	310000	0.70	NS	USD	$C=aP^b$
Hall et al. [36]	Licensing	U.S.	PD	NS	NS	210000	0.70	NS	USD	$C=aP^b$
Hall et al. [36]	Fish& Wildlife	U.S.	NSD	NS	NS	310000	0.96	NS	USD	$C=aP^b$
Hall et al. [36]	Fish& Wildlife	U.S.	NPD	NS	NS	200000	0.96	NS	USD	$C=aP^b$
Hall et al. [36]	Fish& Wildlife	U.S.	PD	NS	NS	83000	0.96	NS	USD	$C=aP^b$
Hall et al. [36]	Recreation	U.S.	NSD	NS	NS	240000	0.97	NS	USD	$C=aP^b$
Hall et al. [36]	Recreation	U.S.	NPD	NS	NS	170000	0.97	NS	USD	$C=aP^b$
Hall et al. [36]	Recreation	U.S.	PD	NS	NS	63000	0.97	NS	USD	$C=aP^b$
Hall et al. [36]	Historical & Archaeological	U.S.	NSD	NS	NS	100000	0.72	NS	USD	$C=aP^b$
Hall et al. [36]	Historical & Archaeological	U.S.	NPD	NS	NS	85000	0.72	NS	USD	$C=aP^b$
Hall et al. [36]	Historical & Archaeological	U.S.	PD	NS	NS	63000	0.72	NS	USD	$C=aP^b$
Hall et al. [36]	Water Quality	U.S.	NSD	NS	NS	400000	0.44	NS	USD	$C=aP^b$

Table E1. (Continued)

Author	Cost Type	Location	Infr. Category	Head Range (m)	Capacity Range (kW)	Estimated value of *a*	Estimated value of b	Estimated value of c	Currency	Cost Model Estimation
Hall et al. [36]	Water Quality	U.S.	NPD	NS	NS	200000	0.44	NS	USD	$C=aP^b$
Hall et al. [36]	Water Quality	U.S.	PD	NS	NS	70000	0.44	NS	USD	$C=aP^b$
Hall et al. [36]	Fish Passage	U.S.	NPD, NSD	NS	NS	130000	0.56	NS	USD	$C=aP^b$
Hall et al. [36]	O&M (fixed)	U.S.	All	NS	NS	24000	0.75	NS	USD	$C=aP^b$
Hall et al. [36]	O&M (variable	U.S.	All	NS	NS	24000	0.8	NS	USD	$C=aP^b$
Hall et al. [36]	Tb (Francis)	U.S.	Unit upgrade	NS	NS	3000000	-0.42	0.71	USD	$C=aP^bH^c$
Hall et al. [36]	Tb (Kaplan)	U.S.	Unit upgrade	NS	NS	4000000	-0.38	0.72	USD	$C=aP^bH^c$
Hall et al. [36]	Tb (Bulb)	U.S.	Unit upgrade	NS	NS	6000000	-0.63	0.86	USD	$C=aP^bH^c$
Hall et al. [36]	G	U.S.	Unit upgrade	NS	NS	3000000	-0.38	0.65	USD	$C=aP^b$
Zhang et al. [12]	Tb	U.S.	NPD, Canal/conduit	NS	100-30000	110168	-0.35	0.70	USD	$C=aP^bH^c$
Zhang et al. [12]	O&M	U.S.	O&M	NS	NS	79894			USD	$C=aP^b$
O'Connor et al. [11]	NS	U.S.	NPD	4.3-109	70-105000	11489245	0.98	-0.24	USD	$C=aP^bH^c$
O'Connor et al. [11]	NS	U.S.	NSD	6-578	3000-824000	9605710	0.98	-0.13	USD	$C=aP^bH^c$
O'Connor et al. [11]	NS	U.S.	Canal/conduit	1.5-578	10-13000	9297820	0.81	-0.10	USD	$C=aP^bH^c$
O'Connor et al. [11]	NS	U.S.	Unit Addition	NS	1400-64000	4613746	0.74	NA	USD	$C=aP^b$
O'Connor et al. [11]	G	U.S.	Generator rewind	NS	12000-2250000	250147	0.82	NA	USD	$C=aP^b$
O'Connor et al. [11]	O&M	U.S.	$O\&M_R$	NS	3000-600000	225417	0.55	NA	USD	$C=aP^b$
O'Connor et al. [11]	O&M	U.S.	$O\&M_{EE}$	NS	NS	0.025	NA	NA	USD	$C=.025*C_{CAP}$

Table E1. (Continued)

Author	Cost Type	Location	Infr. Category	Head Range (m)	Capacity Range (kW)	Estimated value of *a*	Estimated value of b	Estimated value of c	Currency	Cost Model Estimation
Cavazzini et al. [34]	NS	EU	NSD	3-6175	NS	12000	-0.20	0.56	EUR	$C=aP^bH^c$
Cavazzini et al. [34]	Tb (Pelton)	EU	NSD	3-6175	NS	17693	-0.28	0.67	EUR	$C=aP^bH^c$
Cavazzini et al. [34]	Tb (Francis)	EU	NSD	3-6175	NS	25698	-0.13	0.44	EUR	$C=aP^bH^c$
Cavazzini et al. [34]	Tb (Kaplan)	EU	NSD	3-6175	NS	33236	-0.11	0.42	EUR	$C=aP^bH^c$
Cavazzini et al. [34]	Tb (Semi-Kaplan)	EU	NSD	3-6175	NS	19498	-0.11	-0.42	EUR	$C=aP^bH^c$
Zema et al. [94]	NS	Italy	NSD	NS	5-1000	NS	-0.35	0.70	EUR	
USBR [10]	Contingency	Western U.S.	NPD	NS	NS	0.2	NA	NA	USD	*C=a*Construction*
USBR [10]	Sales Tax	Western U.S.	NPD	NS	NS	state defined	NA	NA	USD	*C=a*Construction*
USBR [10]	Engineering & Construction	Western U.S.	Indirect Costs	NS	NS	0.15	NA	NA	USD	*C=a*Construction*
USBR [10]	Mechanical Balance	Western U.S.	NPD	NS	NS	0.2	NA	NA	USD	*C=a*Turbine Costs*
USBR [10]	Electrical Balance	Western U.S.	NPD	NS	NS	0.35	NA	NA	USD	*C=a*GeneratorCosts*
USBR [10]	O&M (fixed)	Western U.S.	NPD	NS	NS	34409.24		0.75	USD	$C=aP^b$
USBR [10]	O&M (variable	Western U.S.	NPD	NS	NS	34409.24		0.8	USD	$C=aP^b$
USBR [10]	FERC Annual Charge	Western U.S.	O&M	NS	NS	NA	NA	NA	USD	$FERC_{Charge(Annual)}=P+112.5*E^c$
USBR [10]	Insurance	Western U.S.	O&M	NS	NS	NA	NA	NA	USD	*C=a*ConstructionCosts*
USBR [10]	Taxes	Western U.S.	O&M	NS	NS	NA	NA	NA	USD	*C=a*ConstructionCosts*

Table E1. (Continued)

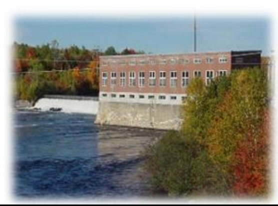
Author	Cost Type	Location	Infr. Category	Head Range (m)	Capacity Range (kW)	Estimated value of *a*	Estimated value of b	Estimated value of c	Currency	Cost Model Estimation
USBR [10]	Management	Western U.S.	O&M	NS	NS	NA	NA	NA	USD	$C=a*ConstructionCosts$
USBR [10]	Major repairs	Western U.S.	O&M	NS	NS	NA	NA	NA	USD	$C=a*ConstructionCosts$
Aggidis et al. [41]	NS	U.K.	NS	2-30	25-990	25000	-0.35	0.65	EUR	$C_{Pr} = a (P/H^c)^b$
Aggidis et al. [41]	NS	U.K.	NS	30-200	25-990	45000	-0.30	0.60	EUR	$C_{Pr} = a (P/H^c)^b$
Singal et al. [39]	Ch, B, Ph, Ps, Tr, W	India	NSD	3-20	NS				INR	Ccivil= C1+C2+C3+C4+C5+C6+C7
Singal et al. [39]	EA, G, Sw, Tb	India	NSD	3-20	NS				INR	$C_{EM}= C_8+C_9+C_{10}+C_{11}$
Singal et al. [39]	Ch, B, Ph, Ps, Tr, W, EA, G, Sw, Tb	India	NSD	3-20	NS				INR	$C_{Total}= 1.13(C_{civil}+C_{EM})$
USACE [9]	Tb (Francis)	U.S.	Unit upgrade	NS	NS	4386508.2	-0.42	0.71	USD	$C=aP^bH^c$
USACE [9]	Tb (Kaplan)	U.S.	Unit upgrade	NS	NS	5848677.6	-0.38	0.72	USD	$C=aP^bH^c$
USACE [9]	Tb (Bulb)	U.S.	Unit upgrade	NS	NS	8773016.4	-0.63	0.86	USD	$C=aP^bH^c$
USACE [9]	G	U.S.	Unit upgrade	NS	NS	4386508.2	-0.38	0.65	USD	
USACE [9]	Contingency	U.S.	NPD	NS	NS	0.2	NA	NA	USD	$C=a*ConstructionCosts$
USACE [9]	Sales Tax	U.S.	NPD	NS	NS	state defined	NA	NA	USD	$C=a*ConstructionCosts$
USACE [9]	Engineering & Construction	U.S.	NPD	NS	NS	0.15	NA	NA	USD	$C=a*ConstructionCosts$
USACE [9]	Mechanical Balance	U.S.	NPD	NS	NS	0.2	NA	NA	USD	$C=a*TurbineCosts$

Table E1. (Continued)

Author	Cost Type	Location	Infr. Category	Head Range (m)	Capacity Range (kW)	Estimated value of *a*	Estimated value of b	Estimated value of c	Currency	Cost Model Estimation
USACE [9]	Electrical Balance	U.S.	NPD	NS	NS	0.35	NA	NA	USD	*C=a*GeneratorCosts*
USACE [9]	Licensing	U.S.	Indirect Costs	NS	NS	453272.51	0.70	NA	USD	$C=aP^b$
USACE [9]	Fish& Wildlife	U.S.	Indirect Costs	NS	NS	294050.62	0.96	NA	USD	$C=aP^b$
USACE [9]	Recreation	U.S.	Indirect Costs	NS	NS	248568.8	0.97	NA	USD	$C=aP^b$
USACE [9]	Historical & Archaeological	U.S.	Indirect Costs	NS	NS	134607.22	0.72	NA	USD	$C=aP^b$
USACE [9]	Water Quality	U.S.	Indirect Costs	NS	NS	294050.62	0.44	NA	USD	$C=aP^b$
USACE [9]	Fish Passage	U.S.	Indirect Costs	NS	NS	19113290.3	0.56	NA	USD	$C=aP^b$
USACE [9]	O&M (fixed)	U.S.	O&M	NS	NS	34409.24	0.75	NS	USD	$C=aP^b$
USACE [9]	O&M (variable	U.S.	O&M	NS	NS	34409.24	0.8	NS	USD	$C=aP^b$
USACE [9]	FERC Annual Charge	Western U.S.	O&M	NS	NS	112.5	NA	NA	USD	$C=P+112.5*E^c$
USACE [9]	Insurance	Western U.S.	O&M	NS	NS	0.003	NA	NA	USD	*C=a*ConstructionCosts*
USACE [9]	Taxes	Western U.S.	O&M	NS	NS	0.012	NA	NA	USD	*C=a*ConstructionCosts*
USACE [9]	Management	Western U.S.	O&M	NS	NS	0.005	NA	NA	USD	*C=a*ConstructionCosts*
USACE [9]	Major repairs	Western U.S.	O&M	NS	NS	0.001	NA	NA	USD	*C=a*ConstructionCosts*

APPENDIX F: DECISION ALTERNATIVES

Table F1. Decision alternatives considered in project cost and performance assessment.

Decision Alternative	Description	Example	Info
Remove dam	The dam is removed completely from the river, allowing water to flow freely downstream and creating greater connectivity for sea-run fish populations, benthic invertebrates, and aquatic vegetation. Hydroelectric dams must be decommissioned prior to removal.		Great Works Dam Removal, Veazie; courtesy of: https://www.maine.gov/dmr/science-research/searun/programs/documents/slideshow.pdf
Improve fish passage	Some type of fish passage structure (e.g., state-of-the-art fish lift/elevator, eel ladder, etc) is installed to improve the passage of fish up or downstream. Improvements to fish passage are typically prescribed by a natural resource agency (e.g., USFWS) and may be required by law (e.g., Endangered Species Act), where owners must shoulder the cost burden or surrender the FERC license.		West Enfield Dam Vertical Slot Fishway Image courtesy of: Sharon Klein
Improve hydropower generation	Hydropower generation capacity is improved by installing new power capacity or by upgrading turbines to larger power capacities. Improvements to hydropower generation capacity must be approved by FERC, and typically require additional environmental studies to demonstrate no negative impacts to fish and wildlife, recreation, water quality, etc.		Ripogenus Dam image courtesy of: https://www.youtube.com/watch?reload=9&v=GqaCyDfaQjw
Improve hydropower generation AND fish passage	Some type of fish passage structure is installed AND hydropower generation capacity is increased. This is a combination decision alternative that incurs the costs of both improving hydropower and improving fish passage.		Ripogenus Dam image courtesy of https://www.youtube.com/watch?reload=9&v=GqaCyDfaQjw, West Enfield Dam Vertical Slot Fishway Image courtesy of: Sharon Klein
Keep and maintain dam	This is the business-as-usual option, where the dam remains in place as-is, and minimal costs are incurred to ensure dam structural integrity and safety compliance. Keeping and maintaining the dam means the owner incurs only regular annual O&M and licensing C_{CAP} costs.		Medway Dam, image courtesy of: https://lowimpacthydro.org/lihi-certificate-65-ferc- no-2666-medway-hydroelectric-project/

APPENDIX G: LIHI-CERTIFIED MAINE DAMS

Table G1. status for Maine dams

LIHI Certification No.	Project Name	River	Status
167	Millinocket-Dolby	West Branch, Penobscot River	Certified
163	Deer Rips/Androscoggin No. 3	Androscoggin River	Certified
141	Mallison Falls	Presumpscot River	Certified
140	Little Falls	Presumpscot River	Certified
139	Gambo	Presumpscot River	Certified
138	Dundee	Presumpscot River	Certified
137	Eel Weir	Presumpscot River	Certified
129	North Gorham	Presumpscot River	Certified
113	Milford	Penobscot River	Certified
79	Benton Falls	Sebasticook River	Certified
72	Automatic	Messalonskee Stream	Certified
67	Stillwater	Penobscot River	Certified
66	Orono	Penobscot River	Certified
65	Medway	Penobscot River	Certified
60	Oakland	Messalonskee Stream	Certified
59	Rice Rips	Messalonskee Stream	Certified
58	Union Gas	Messalonskee Stream	Certified
48	Androscoggin	Androscoggin River	Certified
38	Rumford Falls	Androscoggin River	Certified
10	Worumbo	Androscoggin River	Certified
N/A	Milo	Sebec River	Review in process. **Public comment period ends March 3, 2020**
N/A	American Tissue	Cobbosseecontee Stream	Public comment period closed, awaiting additional information
48	Androscoggin River	Androscoggin River	**Preliminary Decision January 9, 2020.** Appeal period ended February 8, 2020.
167	Millinocket-Dolby	West Branch of the Penobscot River	**Final Decision February 7, 2020**

Source: Low Impact Hydropower Institute [146], [147]

APPENDIX H: EXTENDED NPV SENSITIVITY RESULTS FOR WEST ENFIELD DAM

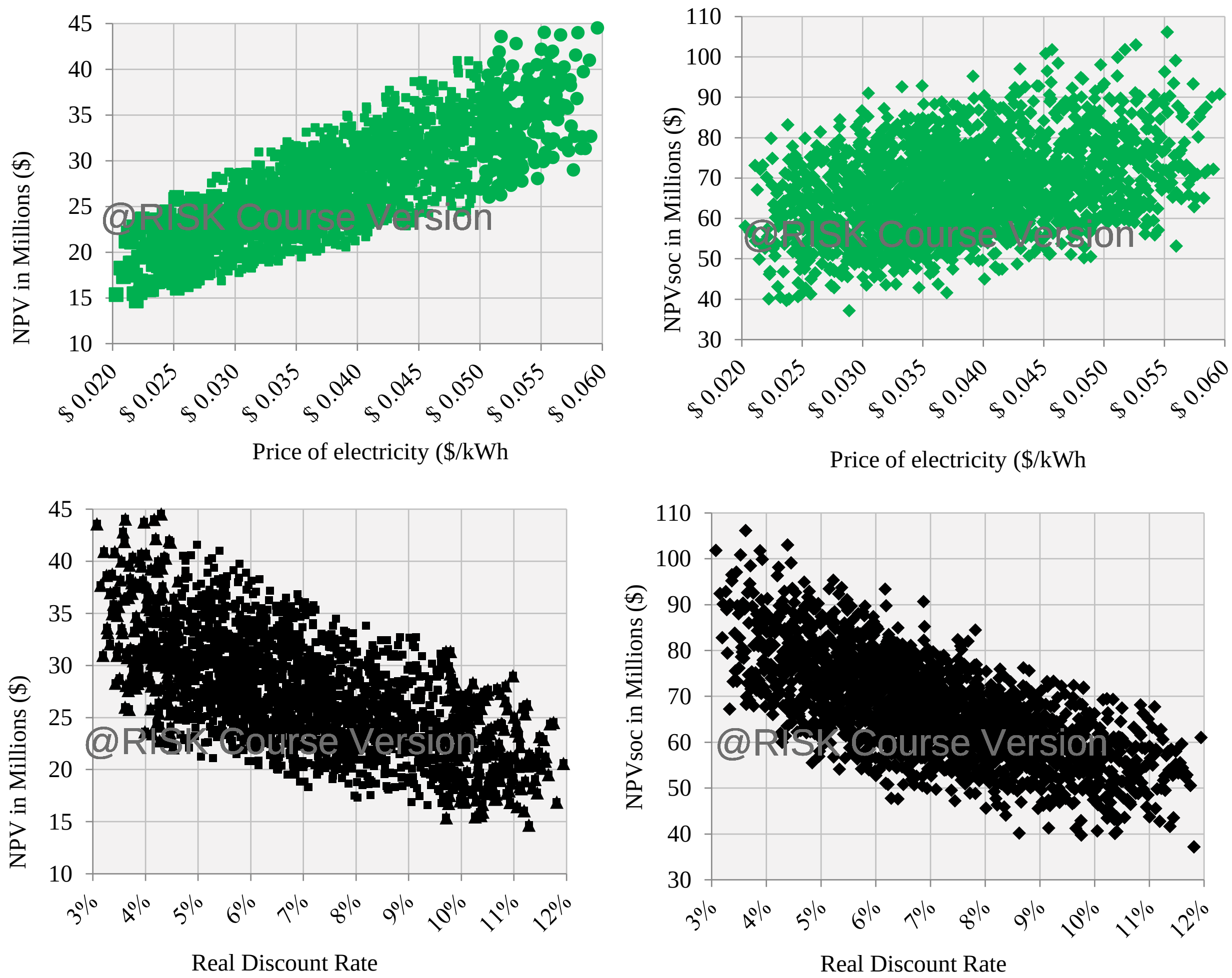


Figure H1. Correlation between 'Keep and Maintain' NPV, NPV_{soc} and wholesale electricity price (P_e) and discount rate (r) for 2,000 simulations.

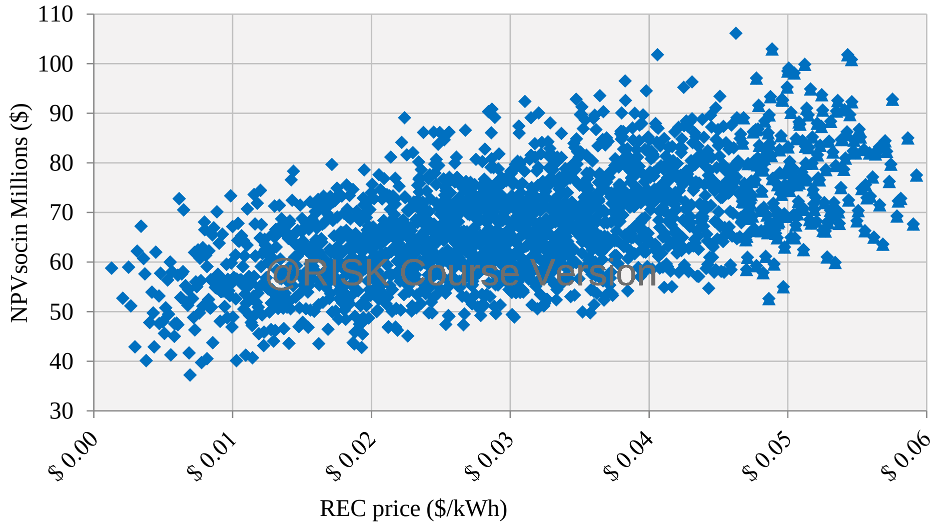


Figure H2. Correlation between 'Keep and Maintain' NPVsoc and REC price for 2,000 simulations.

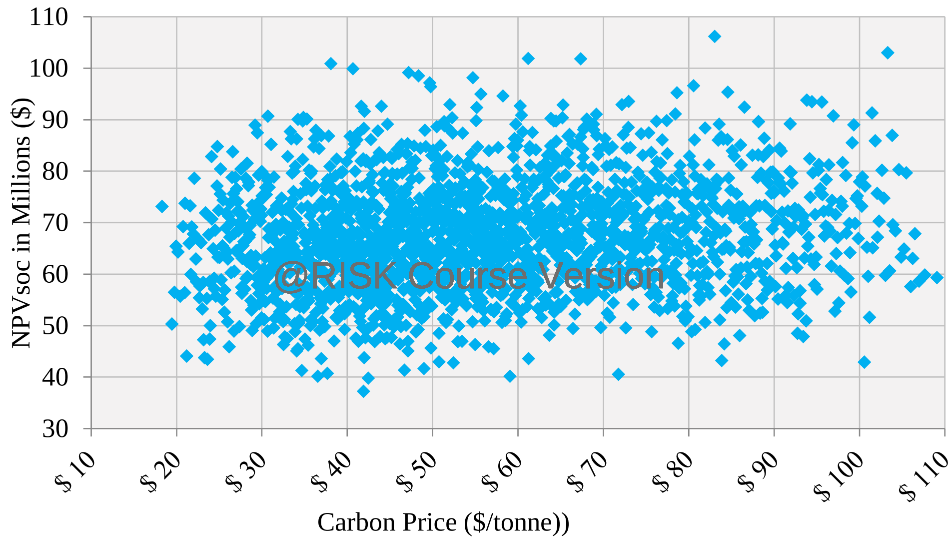


Figure H3. Correlation between 'Keep and Maintain' NPVsoc and carbon price for 2,000 simulations.

APPENDIX I: COMPARISON OF APPLICATION STUDY ATTRIBUTES

Table I1. Criteria and alternatives by study

Author(s)	Loc.	MCDA Type	Social Criteria	Environmental Criteria	Economic Criteria	Technical Criteria	Alternatives
Morimoto [203]	Sri Lanka	WS	No. individuals resettled in dam construction	Biodiversity, hectares forest/agricultural land inundated	Additional cost and generation (kWh) to meet development growth potential, net present value, internal rate of return, benefit cost ratio, electricity generated (GWh/year)	NS	22 possible development opportunities small-scale hydropower plant sites
Klein & Whalley [61]	USA	WS	Fatalities (no./GWh), jobs (FTE/GWh)	Life cycle GHG emissions (gCO2eq/kWh), air pollution (mg/kWh), land use (m2/MWh), water use (L/MWh)	LCOE (USD/kWh)	Capacity factor (%)	13 electricity generation technologies (fossil fuels, nuclear, hydropower, and other renewables)
Mustajoki et al. [59]	Finland	MAVT	Recreational (fishing, boating, shore use, landscape)	Nature (shores, birds, fish, river)	Commerce (fishing, tourism), industry (hydropower, water supply, floating)	Flood damage (agricultural, recreational, industry)	4 lake level/flow release regulation schemes (business-as-usual, recreational, fishing, and "natural")
Cai et al. [86]	North China	MAVT	Employment rate	Average biochemical oxygen demand (BOD) discharge (i.e., water quality)	Gross domestic product (GDP), project cost (USD)	Food production (per capita)	6 plans for water development and management (including reservoir storage changes, sewage treatment, agricultural and industrial water savings, and inter-basin transfer)

Table I1. (Continued)

Author(s)	Loc.	MCDA Type	Social Criteria	Environmental Criteria	Economic Criteria	Technical Criteria	Alternatives
Marttunen & Hämäläinen [200]	Finland	MAVT	Recreation (EUR lost by water level change)	Aquatic environment (vegetation area (km2), fish recruits (% change), bird nests damaged (no.), macrophytes (% change), zoobenthos (% change), salmonid flow decreases (m3/s))	Industry (hydropower value (EUR), timber floating days affected (no.), paper production days affected (no.)), small companies (water draw down (m), rafting days affected (no.))	Flood damage cost (to agricultural, building and other structures)	3 lake level/flow release regulation schemes (recreational, ecological, hydro)
Trutnevyte et al. [87]	Switzer-land	MAVT	Employment (jobs/MWh/yr)	Air pollution (PM-10 mg/MWh), GHG emissions (thousands tons CO_{2eq}/yr), landscape quality score (1/MWh/yr)	Average annual cost (millions CHF/yr)	End consumption (MWh_{eq}/MWh)	6 'visions' ("Preparation for high oil prices", "energy independence", "energy production", "cost-effective supply", "efficient supply", "secure supply") each described by 15 heat/ electricity technologies (wind, hydro, solar, district heating, heat pumps, wood chips, efficiency measures, etc.)
Bertsch & Fitchner [88]	Germany	MAVT	Noise impacts (perceived, point scale), health impacts (perceived, point scale)	CO_2 emissions (millions tons CO_2/yr), landscape changes (perceived, point scale)	Total system costs (billions EUR)	Grid transmission bottlenecks (% lines used to limit)	5 policy combinations (renewables injection and grid expansion)

Table I1. (Continued)

Author(s)	Loc.	MCDA Type	Social Criteria	Environmental Criteria	Economic Criteria	Technical Criteria	Alternatives
Kowalski et al. [89]	Austria	PROMETHEE	Regional self-determinacy (qualitative), social cohesion (qualitative), employment (qualitative), noise (qualitative), social justice (qualitative)	CO2 emissions (tons/TJ), air pollution (kg/TJ), water quality pollutants (g/TJ), landscape quality (qualitative)	Fixed & variable costs (EUR/TJ), effect on public spending (qualitative)	Electricity generation (GWh), heat production (PJ), fuel inputs (GJ/TJ), material inputs (kg/TJ), supply security (qualitative), import independence (qualitative), technology diversity (qualitative), technological advantage (qualitative), energy security (qualitative)	5 national scenarios for (a) heat (heat pump, geothermal, biogas, biomass, solar thermal) and (b) electricity (geothermal, biogas, biomass, solar PV, wind, small hydro); 4 local-level scenarios for (a) heat (solar thermal, wood logs, biomass district heat, heat pump, pellets, wood chips) and (b) electricity (small hydro, biogas, solar PV)
Pictet & Bollinger [204]	NS	PROMETHEE	NS	NS	NS	NS	NS
Marttunen & Hämäläinen [90]	Finland	AHP	Farms receiving project benefits (no.), buildings in the flood zone (no.), fishermen impacted (no.), losses in ground water (m^3/day), mercury content in fish (mg/kg), land required for dredged sediment disposal (km^2); recreation (years of construction period)	Water quality (soil suspended (mg/liter)), changes in both spawning (%) and river habitats (stream (%), rapids (%), aquatic vegetation (%))	Private and commercial economic benefits from agriculture (millions FIM), hydropower (millions FIM), construction (millions FIM), government spending (millions FIM), employment (person-years)	NS	4 development/dredging projects in different extents of the river (the channel, the middle part of the river, lower part of the river, complete project)

Table I1. (Continued)

Author(s)	Loc.	MCDA Type	Social Criteria	Environmental Criteria	Economic Criteria	Technical Criteria	Alternatives
Hämäläinen et al. [205]	Finland	AHP	Recreation (water level change)	Landscape (revealed mud), nature (width of riparian zone), water quality (turbidity)	Hydropower (income increase), fishing (catch value), flood damage (costs), water supply (costs), transportation (profits), tourism (profits)	NS	5 lake level management schemes (not defined)
Antunes et al. [91]	Portugal	AHP	Employment (no. jobs), social equity (qualitative), community participation (qualitative), rural livelihoods (qualitative)	Nitrate pollution (mg NO_3/l), water quality (mg O_2/l), water use sustainability (unitless), erosion risk (ton/ha/yr), biodiversity (qualitative), soil salinization (qualitative)	"Economic productivity of water" (EUR/m^3), financial costs (EUR/yr)	Water productivity (ton/m^3), irrigation consumptive use coefficient (unitless), resilience metrics (e.g. security of water supply and flexibility, both qualitative), feasibility metrics (technical/operational, political/institutional, affordability, all qualitative)	6 irrigation schemes: business as usual, rehabilitation of existing system, modernization of the system, improved technologies, integrated water resource management, and changes in agricultural practices
Stein [206]	USA	AHP	Jobs (no. new jobs), net import energy (%), fuel reserve (yrs)	External costs ($), loss of life (expected no.)	Overnight costs (USD/kW), fixed & variable O&M (USD/MWh), fuel costs (USD/MBtu)	Average efficiency (%), capacity factor (%)	9 electricity generation technologies (fossil fuels, nuclear, hydropower, and other renewables)
Kallis et al. [92]	Spain	NAIADE	NS	NS	NS	NS	NS

Table I1. (Continued)

Author(s)	Loc.	MCDA Type	Social Criteria	Environmental Criteria	Economic Criteria	Technical Criteria	Alternatives
Salgado et al. [93]	Spain	NAIADE	Institutional difficulty, social acceptance, equitable distribution of costs and benefits	Ecological and ecosystem impacts,	Costs of implementation and operation, effects on employment and general economic activity	Project timeline(s)	7 projects: heightening a dam, using desalinated water, reusing wastewater, modernizing irrigation systems, systematic allocation of groundwater, improved efficiency in urban water supply, spatial policies for urban development (reforestation of the basin), and business-as-usual
Simonovic & Bender [58]	Canada	CPSS	Employment rate, population density, cultural heritage, medical capacity (health risk)	Habitat suitability, species population, species range, land cover, land use	Benefit cost ratio, inflation rate, energy price, NPV, discount rate, water price, domestic demand for water, construction cost, operation and maintenance costs, annual benefits	Structure lifespan, reservoir volume, energy capacity, water supply reliability, flow discharge, flow morphology, flow runoff coefficient, shoreline erosion	NS
Van Eeten et al. [207]	USA	SDS	Recreation (suitability for boating)	Fish habitat suitability, water quality (algae concentration, dissolved oxygen, nitrogen), erosion potential (area loss)	Expected economic flood damage, cost of water supply, hydropower income	Hydropower generation measured (kWh), water supply quantity	NS
Kallis et al. [92]	Portugal	SDS	NS	NS	Opportunity costs to landowners from conservation restrictions, sustainable development	Water salinization, sediment inputs	Local projects: saltmarsh restoration and wastewater treatment plant construction

Table I1. (Continued)

Author(s)	Loc.	MCDA Type	Social Criteria	Environmental Criteria	Economic Criteria	Technical Criteria	Alternatives
Manthrithilake & Liyanagama [208]	Sri Lanka	SDS	Household use	Environmental regulation	Agricultural (irrigation) and industrial (hydropower) needs	Minimum flows, trans-basin diversions, other uses	NS
Brown et al. [57]	NS	IDAM	Social cohesion (unitless, qualitative), cultural change (no. sites), health (contamination days/yr)	Water retention (time), natural value (unitless), downstream tributaries (no.) biodiversity (% endangered species), dewatered river downstream (km), CO2 equivalent to coal (lbs/MW), flood protection (return year interval), site stability (unitless, qualitative), reservoir surface area (km2)	Non-agricultural economic activity (USD), agricultural economic activity (USD), relocation cost (USD), hydropower market value (USD), hedonic value of recreation and landscape (USD), transportation (USD)	Downstream riparian population (no.), downstream irrigation (km), political boundaries (no.), existing dam storage capacity (km3), agreements (index), historical stability/tensions (unitless, qualitative), domestic governance (unitless, qualitative), socio-economic impacts (unitless, qualitative)	Dam development scenarios (NS)

Table I1. (Continued)

Author(s)	Loc.	MCDA Type	Social Criteria	Environmental Criteria	Economic Criteria	Technical Criteria	Alternatives
Tullos et al. [56]	China	IDAM	Social capital (unitless, qualitative), cultural heritage (no. sites), health (contamination days/yr), access to hydropower (unitless, qualitative)	Water quality (change over time), biodiversity (habitat quality index), impact area (index of habitat quantity), sediment (% basin contributing sediment to dam), natural flows (changes to flood frequency, qualitative), climate change and air quality (CO_{2eq}/MW/km reservoir) , landscape stability (weight and depth of reservoir, erosion, landslide hazard)	Income (average value derived from surveys and census data), wealth (housing and land values), macro impacts (cost of resettlement, commercial cost of hydropower)	Basin population affected (%), political complexity (no. and type of political boundaries crossed by a project), legal framework (unitless, qualitative), domestic governance (unitless, qualitative), political stability (unitless, qualitative), socio-economic impacts (unitless, qualitative)	Development projects, including: (1) large main-stem dam, (2) multiple smaller tributary dams

Table I1. (Continued)

Author(s)	Loc.	MCDA Type	Social Criteria	Environmental Criteria	Economic Criteria	Technical Criteria	Alternatives
Kallis et al. [92]	Greece	Other	Water quality	NS	Tourism development	Water quantity	Planning scenarios: business-as-usual (regional tourism growth); economic modernization with privatized utilities and updated technologies; balance between environment, development, and water conservation with local administration; self-sufficiency through grassroots efforts toward reduced water consumption; and local administration of balanced development/environment /water conservation with self-sufficiency, grassroots efforts, and updated technologies

Table I1. (Continued)

Author(s)	Loc.	MCDA Type	Social Criteria	Environmental Criteria	Economic Criteria	Technical Criteria	Alternatives
Xenarios & Tziritis [201]	Greece	Other	Degradation of water (climate change, pesticide usage, river pollution, infrastructure scarcity, sewage, value of freshwater), environmental (birds, aesthetics, phosphates, urban development), conflict amongst/between groups, future scenarios (pessimism, optimism, institutional change, industrial expansion, economic development)	Biological (chlorophyll, phytoplankton, zooplankton, macrophytes, benthic macroinvertebrates, microbial load), general (landslides, overfishing, mussel excess farming, domestic waste disposal, over drilling, sand extraction, reduction of diversity, wetland area loss, vegetation loss, health problems)	Socio-economic (environmental risk, agriculture, fisheries, industry, cost-benefit analysis)	Physical (precipitation, evaporation, catchment discharge, air temp, water temp, suspended solids, tides, drainage, flooding), heavy metals (lindane, benzoapyrene, detergents, etc.), chemicals (total nitrogen, organic carbon, nitrates, ammonia, phosphorous, water salinization), relation to the state (controls, interest, participatory approaches, motivation, awareness)	NS
Tompkins et al. [170]	UK	Other	Power to act, responsibility for action, equity of actions (risk management)	Climate change pressure (flood risk, erosion and sedimentation, sea level rise/flooding, roughness of seas, tide level changes, wind speed/direction)	Cost	Timing of actions, effectiveness, acceptability of actions	4 management option types: central anticipatory (top-down action, early), central reactive (top-down action in response to change), local anticipatory (bottom-up action early), local reactive (bottom-up in response to change)
Madani [209]	USA	Other	NS	Endangered species	Revenue from hydropower generation (USD), fish penalties	Reservoir capacity, max/min instream flows (cfs), hydropower capacity (MWh)	NS

APPENDIX J: INTERVIEW PROTOCOL AND INTERVIEW CODEBOOK

Interview Code: ______ ______ ______ ______ (Intervieweer initials) (Month) (Day) (Year) Time: _________________ *Version 0.3.1*

Key: (☆ Priority question) (= Specific wording important) (↻ Wait for open-ended response before prompting specifics)

Introductory question

☆ 1. How does your work relate to dams? *Explore: To what extent have you been personally involved in decision making about dams? How long have you been doing this work?*

I. Context for dam decision making in general

☆ = 2. What are some of the most common arguments you have heard to keep or remove a dam?

☆ ↻ 3. Besides the arguments you've mentioned, what other important issues have you noticed related to dams? (*Ex: Ecological, hydrological, or geological.) Explore: How about human communities? Social or environmental justice?*

4. [If involved in decision making] when deciding what to do with a dam, what options do you typically consider? *Explore: How do you identify these options? Individual dams or groups of dams? What constrains your decisions?*

Organizational decision alternatives

5. When deciding what to do with a dam, what options does [your organization] typically consider? (Examples: Removal? Retrofit with fish passage? Relicensing?) *Explore: One dam at a time or multiple dams at the same time? How might these different decision alternatives affect the river system (negatively, positively)?*

6. [Summarize the options mentioned] How do you identify which of these options are available for a dam?

= 7. What significant constraints are there on your decisions? *(Ex. Laws, regulations, organizational mandates)*

6. How would you characterize the level of influence various groups have had in the decision making process? To what extent was this equal or unequal?

7. Has there been a process of public involvement, and if so, what has this process looked like?

☆ = 8. What were the outcomes in this case? Have there been unforeseen positive or negative consequences?

☆ 9. What are the key ingredients for a successful process? Conversely, what are key complicating factors?

III. Types of information and ways of communicating

☆ 10. What types of information do you use in your dam-related work? *Explore: Do you use scientific information? If so, what is the source? Are you satisfied with the available information/data (its quality and/or availability)?*

11. In your experience, in public engagement processes, how has the communication between scientists and the public gone? What has been effective and what hasn't worked well? Is the public able to offer input and feedback?

12. What has been the role of visualizations in the public process? *Explore: Can you describe the visualizations and the sorts of data and input that contributed to them? How did they impact decisions made?*

Conclusion/wrap-up

☆ 13. What outcomes from the Future of Dams project would be most useful to you to support your decision making? *Explore: Would you like to receive information about the Future of Dams in the future? [If so] how?*

☆ 14. Who else should we talk to?

☆ 15. Are there other questions we should be asking people about dams? [If so] what are these questions?

☆ 16. Is there anything else you would like to offer this conversation that I didn't ask about?

Table J1. Parent and Child Codes (Nodes) with Descriptions

Parent node	Child1 node	Child2 node	Description
Criteria	Aesthetics		Aesthetic characteristics of the river.
	Fish		Indication of fish-related issues, rather than specific species.
		Access	Access to fish passage facilities.
		Survival	Survival of fish through turbines, over spillway, or more generally moving up and downstream within the waterway.
		Stocking	Stocking of fish spp. in rivers or lakes, for recreational angling or population support (e.g. salmon, trout).
		Harvesters	Fishers, referenced as "harvesters" by some interviewees; defined as both commercially licensed fishers taking aquatic species from the waterway for sale at market, and recreationally licensed fishers supplementing their groceries.
	Water Quality		Referring to pollution in the water, nutrient levels, dissolved oxygen, pH, turbidity (suspended solids), or heavy metal content.
	Water Quantity		For human use (e.g. drinking water, drywells for firefighting, recreation, and other residential use). Includes references to reservoir surface area.
	Employment		Any employment related to: dam construction; civil works or electromechanical equipment manufacturing; hydropower developing; consulting on technical, economic, or environmental impact assessment; retail; or tourism related to dams.
	Land Use		Human use of land for agriculture (growing crops), commercial (for-profit business such as offices, shopping malls, or restaurants), recreation (leisure), residential (apartments, houses), or transportation (avenues or conduits for travel)
	Sediment		Anything relating to sediment issues with a dam
		Buildup	Accumulation of solid particulate behind a dam
		Release	Flow of particulate from behind a dam to lower river, as a result of overtopping, or breach (either accidental failure or intentional removal)
		Toxicity	The measure of the amount of dangerous chemicals a certain amount of sediment contains
		Removal	Removal of sediment behind a dam for maintenance
	Cost		Any cost that is incurred from implementation of an alternative or decision about a dam.

Table J1. (Continued)

Parent node	Child1 node	Child2 node	Description
		Project Cost	Project costs (overall or non-specified), typically relating to hydropower projects, rather than the construction of new dams. Could also include decommissioning or removal costs.
		Capital cost	The amount of money it took to build an existing dam or would take to build a future dam.
		O&M Cost	Any cost that occurs from the operations or maintenance of a dam while it is in use.
		Revenue	Money coming into a business, organization, or community because of a dam (whether through power generation or indirect means).
		Profit	Revenues minus costs, but only if a net financial gain
		Licensing fees	Fees for renewing or first-time licensing of dams
		Permitting fees	Fees for environmental permits
		Certification fees	Fees toward certification (renewable energy or low-impact)
		Asset value	Financial value of a hydropower or dam development to provided monetary gain.
	Hydropower Production		Any mention of the production of hydropower or electricity generation
		Cavitation	Instant, extreme pressure change within turbine casing that can cause blades to pock or bubble, causing lasting damage; associated with fish kills (juvenile alewives and shad may experience eyeballs bursting)
		Certification	Certification of hydropower dams as low-impact by Low Impact Hydropower Institute (LIHI) or Green-e or other Renewable Portfolio Standard-related program
		O&M	Regular operation and maintenance of hydropower dams
		Energy	Electricity produced for consumption over a certain amount of time (will be seen as kWh, MWh, GWh etc.).
		Power	The maximum rated hydroelectric capacity of the river/impoundment/structure/turbine assemblage (will be seen as kW, MW, GW etc.)
	Invasive Species		Mention of invasive or non-native species which may be encroaching on native species' habitat or competing for food
	Air Pollution		Emissions of pollutants to the air that are not classified as greenhouse gases (e.g. sulfur oxide, nitrogen oxide, particulates, asthma, pollution, emissions)

Table J1. (Continued)

Parent node	Child1 node	Child2 node	Description
	Climate changes		Climate-related changes, such as temperature (long-term change in average temperature for a season or time of year in a region), tide (long-term changes in sea level or storm surge height, as relevant to head of tide dams), weather (long-term changes in patterns of weather events, including flooding).
		GHG emissions	GHGs (greenhouse gas emissions)
	Indigenous Cultural Heritage		Long-term cultural and archaeological heritage, distriguished from historical value by a decolonized, geological historical perspective
	Industrial Historical Value		Long-term historical heritage or landmark value
	Property Value		Value specific to home and property value (whether in reference to hedonic assessment or more anecdotal concerns over changes in value of lake-adjacent camps
	Flow		Any mention of river flows
		Deviation from Normal	Impact dam has on natural flow of the river (anecdotal or empirical, refers to the dynamic movement of water)
		Flood Control	Function of dam as controlling flow of water during floods
		Physiography	Mention of river physiography as it impacts
		Control Ice flow	
	Reservoir Levels		Refers to static water levels in reservoirs
	Ecology		Mention of ecological function or value, typically in reference to ecological health or consideration of the environment as supporting diverse life forms
	Economic Development		Potential for boosting the economy, whether through retail, tourism, recreation, or community. Mentions of enhanced capacity of the economy or local area to handle more activity
	Economic Feasibility		Feasibility of decision alternatives from an economic perspective; deals with the availability of funds or grants to carry out specific projects
	Technical Feasibility		Feasibility of decision alternatives from an objective, technical or engineering perspective
	Recreation		Use of river or reservoir for recreational purposes (includes kayaking, paddle boarding, canoeing, sailing, motor boating, rowing, fishing, swimming, or other purposes)

Table J1. (Continued)

Parent node	Child1 node	Child2 node	Description
	Hazard Level		State designated dam hazard level (formerly safety)
	Endangered Species		
Alternatives	Decommission		Decommission of existing hydropower facilities (e.g. open the gates and let the river flow through)
	Fish Passage Facilities		Addition of fish passage facilities at existing dam or impoundment
		Lift	Fish lift or elevator
		Ladder	Any fish ladder
		Nature-like	Nature-like fishways
		Denil	Specific fish passage type
		Trap & Transport	strategy for fish mitigation that involves trapping fish downstream and trucking them elsewhere on the river (usually upstream). Also called trap-and-truck
	Maintenance		physical repairs or maintenance to the dam
	Hydro retrofit		any hydropower retrofit project
		Expand Capacity	Hydropower generation-specific alternative
		Install Turbines	Installation of hydroelectric turbines at existing non-powered dam or impoundment
		Trashrack	change in the size of trashrack screen, shape, or placement
		Replace/Upgrade Turbine	upgrades to non-electromechanical equipment, such as physical dam structure or abutments.
			replacement or upgrade of existing turbine to enhance efficiency of electricity generation, reduce cavitation, or limit fish kills from pressure change or blade hits
	Keep Dam		Keep existing dam; status quo alternative
	New Dam Construction		This one is not so much realistic, but may be reflective of citizen and even local government perceptions of an alternative. Includes run of river dams (little to no water storage, dam operated as flow in=flow out), storage (storage hydro dams store large amounts of water in a reservoir and produce electricity when this water is released through a turbine), non-powered (any type of dam built with no power generation system (overflow, masonry, gravity, etc.)
	Refurbishment		Repairs, whether structural (fixes to concrete, wooden, or earthen parts of a dam's civil works) or electromechanical related (fixes to power generation equipment, like turbines)
	Removal		Removal of the dam

APPENDIX K: SUPPLEMENTAL MATERIALS FOR WORKSHOPS

This appendix contains screenshots of the supplemental materials that participants saw in each workshop, in chronological/study order.

1. Workshop 1: June 2018 FOD Researchers

Researcher participants were invited to attend the optional workshop prior to a team meeting the following day. Participants who replied "yes" to an RSVP request were emailed: 1) a Google Drive link with a packet of information to help them prep (including information on participant rights and a consent form) and 2) a pre-survey.

1.1. FOD Pre-Meeting Workshop Agenda

This Participatory Multi-Criteria Decision Analysis (PMCDA) workshop will be conducted by Sharon Klein, Emma Fox, and Sam Roy on Monday, June 4th, prior to the All-Team meeting at the University of Maine. In this workshop, we will test an Excel-based decision tool and stakeholder engagement process. We need feedback to create the most effective workshop design for dam decision-makers. We will test processes for individual and group interaction with the MCDA model, which is based on Analytical Hierarchy Process and multi-objective programming using Production Possibility Frontiers (PPFs).

After the individual and group activities, there will be some workshop evaluation activities and we will reflect on what was learned, what was helpful, and what needs to be changed for our upcoming workshops with Penobscot and Union River watershed stakeholders. We estimate that the workshop will take between 4 and 6 hours. In this packet, please find the following documents (listed in the order they should be read):

- IRB Form: all participants need to download and sign prior to the workshop, *email to emma.fox@maine.edu with subject line "Mock Workshop IRB"*
- Pre-Survey: participants should fill out the pre-survey prior to the workshop

- Agenda (next page): plan for activities and timing
- Instructional Slides: details about PPFs and MCDA (download for best viewing)
- Instructional Video: walks participants through the slides and explains the model
- Decision Scenario Description: describes the hypothetical but realistic scenario under which participants will be asked to consider criteria and select a decision alternative
- Excel model: participants should download and enable Macros, VBA. Participants with Macs will need to use a Virtual Machine with Windows or borrow a PC for the workshop. *Please email emma.fox@maine.edu by 6/01/18 if you will need to borrow a PC.*
- (Optional) supplemental materials: AHP Methods
- Post-Survey (please wait until after the workshop has concluded to start answering this)

FOD Mock Workshop Agenda

Where: Senator George J. Mitchell Center for Sustainability Solutions

When: June 4th at the University of Maine's Mitchell Center, from 2pm to 8pm.

Schedule:

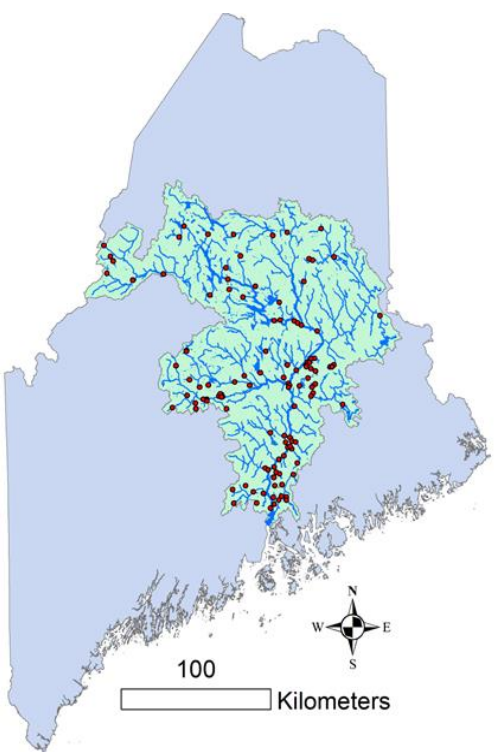
- 2:00pm-2:15pm Arrive and **Sign In**
- 2:15pm-2:30pm Introductions: Everyone describes their interest in participating. Sign consent forms, fill out pre-survey.
- 2:30pm-3:00pm Presentation: Overview of the agenda for the day, description of the purpose of the activity, introduction to PPFs and MCDA, and instructions for doing AHP.
- 3:00pm- 3:45pm AHP Round 1: Guided, but individual; participants explore pairwise comparisons and make rating decisions on their own.
- 3:45pm-4:15pm Snacks Break
- 4:15pm-5:00pm Maps, Discussion Round 1: Instruction on how to look at maps. Participants view individual results maps in a "pair share". Full group report out.
- 5:00pm - 6:00pm AHP Round 2: The second round of AHP is performed as a group; participants negotiate decisions about ratings for pairwise comparisons.
- 6:00pm-6:30pm Dinner
- 6:30pm - 7:00pm Discussion Round 2: Discuss group negotiation experience
- 7:00pm -7:30pm Debrief with Maps: Debrief group result and discuss similarities and differences with individual outcomes.
- 7:30pm - 8:00pm Discussion Round 3: Reflect on PPF-based MCDA output, and overall experience.

1.2. Watershed Scenario Description

Participants were provided with a scenario description orienting them to the Penobscot Watershed, because we had several FOD researcher participants from out of state. The scenario description provided individual and group directions, as well as a tale with Saaty's Fundamental Scale for reference.

Penobscot Dam Decisions Workshop

Picture the Penobscot watershed: rain falls and runs downhill toward tributaries which flow into the river, which itself flows into the Gulf of Maine. This watershed is home to valuable ecosystem services, including pristine natural lakes, clean water sources, and significant biodiversity, including several sea-run fish species (e.g. Atlantic salmon, American eel, Blueback herring, and Alewife). The Penobscot and its tributaries are home to many dams that also provide services, including reservoirs for drinking water and recreation, flood protection, and generation of reliable, on-demand renewable hydropower, critical to reducing emissions that contribute to climate change and poor human health. However, similar to dams across the United States, the dams in this watershed are aging and pose potential safety hazards, increasing the need for regular maintenance or more extensive repair. Dams may interrupt flows and prevent sea-run fish passage, contributing (along with poor water quality, increased predation, and climate change) to large population declines. Dams have long threatened indigenous cultural heritage, while also contributing to post-industrial community identity over the last two centuries.



Map courtesy of Sam Roy (2017)

Individual Decision Scenario

For this activity, imagine that the future of the Penobscot watershed (pictured here, Roy, 2017) is directly in *your* hands. You are personally tasked with using your professional expertise to make sustainable dam decisions for the Penobscot watershed. *Your task is to consider each of the four <u>decision alternatives</u> for hydropower dams:* (1) capacity expansion at existing hydroelectric dams, (2) dam removal, (3) fish passage facility upgrades at powered and non-powered dams, or (4) refurbishment of current dam facilities (turbine replacement or upgrade and fish passage improvement). *Please also consider the following four <u>decision criteria</u>:* (1) sea-run fish biomass, (2) annual electricity generation, (3) reservoir surface area (a proxy for storage and recreation opportunities), and (4) total project costs for each alternative.

Directions: Please use the Decision Support Tool program. This tool uses a method called Analytical Hierarchy Process Multi-criteria Decision Analysis to compare and rank potential management decision alternatives (e.g. remove a dam, expand existing hydropower capacity, add fish passage facilities at a dam) based on a fixed set of criteria (e.g. annual electricity generation, fish biomass, reservoir surface area). It asks the user to make pairwise comparisons to help rank these management alternatives. *The tool will calculate your results automatically*.*

*NOTE: the program does not make a decision for the user; rather, the result is a prioritized list of

The Fundamental Scale for Pairwise Comparisons		
Intensity of Importance	**Definition**	**Explanation**
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment moderately favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
Intensities of 2, 4, 6, and 8 can be used to express intermediate values. Intensities of 1.1, 1.2, 1.3, etc. can be used for elements that are very close in importance.		

Table 7. Rating scale developed by Thomas Saaty (2016)

possible decision options, ranked using user inputs (preferences and priorities).

1. Press “START” to begin and follow the directions provided.
2. Start with the **Criterion 1: Sea run fish biomass** and work your way through the pairwise comparisons (steps 1-6), using the Fundamental Scale to rate each alternative 1-9, where 1 indicates equal preferences between alternatives and 9 indicates extreme importance of the alternative, as compared to the base alternative. The alternative (a) is the base against which you will compare the alternative (b). Rate the alternatives based on their performance under the criterion using the Fundamental Scale. For example, in comparing (a) adding fish passage facilities to (b) adding hydropower capacity under the criterion of annual electricity generation, you might select "3", where (b) is moderately favored over (a). Press “Next step” to advance through each page of the section.
3. Begin the second section, **Criterion 2: Annual electricity generation** and work your way through the pairwise comparisons (steps 7-12). Press “Next step” to advance.
4. Work through the third section, **Criterion 3: Reservoir surface area** and rate each of the pairwise comparisons (steps 13-18). Press “Next step” to advance.
5. Work through the fourth section, **Criterion 4: Project costs** and rate each of the pairwise comparisons (steps 19-24). Press “Next step” to advance.
6. ***ATTENTION***: this next section is different. Instead of comparing decision alternatives in pairs, isolated on a single criterion, you will be comparing criteria directly against one another in pairs. Please consider only the pure criteria in front of you (no decision alternatives attached). The criterion (a) is the base against which you will compare the criterion (b). Rate the alternatives based on your expertise and preferences using the Fundamental Scale. Work through the final section of the tool, **Criteria Matrix**, and rate each of the pure criteria against one another.
7. Press “FINISH” and view the results. See how your decision alternatives rank against one another, based on the scores you entered into the tool. Press “...show me the math” if you are interested in seeing the model calculations for yourself!

Group Decision Scenario

For this activity, you are no longer operating in a vacuum and making decisions on your own. Instead, imagine that the future of the Penobscot watershed depends on the participants in this workshop. You and others in this room are tasked with making sustainable dam decisions for the Penobscot watershed. *The group's task is to consider the same four* <u>*decision alternatives*</u> *for hydropower dams:* (1) capacity expansion at existing hydroelectric dams, (2) dam removal, (3) fish passage facility upgrades at powered and non-powered dams, or (4) refurbishment of current dam facilities (turbine replacement or upgrade and fish passage improvement). *Do not forget to consider the following four* <u>*decision criteria*</u>*:* (1) sea-run fish biomass, (2) annual electricity generation, (3) reservoir surface area (a proxy for storage and recreation opportunities), and (4) total project costs for each alternative.

Directions: Please use the Decision Support Tool program. This tool uses a method called Analytical Hierarchy Process Multi-criteria Decision Analysis to compare and rank potential management decision alternatives (e.g. remove a dam, expand existing hydropower capacity, add fish passage facilities at a dam) based on a fixed set of criteria (e.g. annual electricity generation, fish biomass, reservoir surface area). *The tool will calculate your results automatically*.* The facilitator will enter the value <u>after the group has come to a consensus</u>. If no consensus is reached after a reasonable amount of time, the average of all participants' individual scores will be used as a comparison value. *You will not enter data for this activity.* After all of the pairwise comparison values have been determined, the facilitator will show the results and the group will have a chance to change any values that do not "feel right".

*NOTE: the program does not make a decision for the user; rather, the result is a prioritized list of possible decision options, ranked using user inputs (preferences and priorities).

1. Start with the **Criterion 1: Sea run fish biomass** and work through the pairwise comparisons (steps 1-6, press "Next step" to advance). The alternative (a) is the base against which you will compare the alternative (b). Rate the alternatives based on their performance under the criterion

using the Fundamental Scale. For example, in comparing (a) adding fish passage facilities to (b) adding hydropower capacity under the criterion of annual electricity generation, you might select "3", where (b) is moderately favored over (a).

2. Begin the second section, **Criterion 2: Annual electricity generation** and work through the pairwise comparisons (steps 7-12).
3. Work through the third section, **Criterion 3: Reservoir surface area** and rate each of the pairwise comparisons (steps 13-18).
4. Work through the fourth section, **Criterion 4: Project costs** and rate each of the pairwise comparisons (steps 19-24)
5. After all of the pairwise comparison matrices are filled out, the group may discuss the criteria comparison matrix. If there is no time or consensus is not reached within a reasonable amount of time, the individual participant results will be averaged and used. ***ATTENTION***: this section is different. Instead of comparing decision alternatives in pairs, isolated on a single criterion, the group will be comparing criteria directly against one another in pairs. Please consider only the pure criteria given in pairs (no decision alternatives attached). The criterion (a) is the base against which you will compare the criterion (b).
6. Check to see if the group scores were consistent. If they are not, the facilitator will ask the group to revisit the pairwise comparisons and check to see if group priorities conflict with each other in any way. Conflicting priorities may result in inconsistency if they are outside a margin of error.
7. The facilitator will show the final group results. See how the group decision alternatives rank against one another, based on the scores entered into the tool. The group will have time to discuss how the decision alternatives rank against one another, based on the group scores. The group may want to reflect on the similarities and differences with the individual decision activity.

References

Roy, S. (2017). “Damming Decisions: Searching for sustainable solutions in New England Rivers”. Presentation, Senator George J. Mitchell Center for Sustainability Solutions University of Maine. Orono, ME.

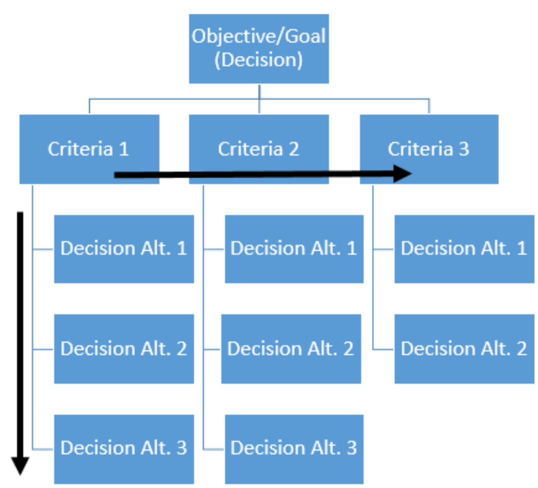
Saaty, T. L. (2016). The Analytic Hierarchy and Analytic Network Processes for the Measurement of Intangible Criteria and for Decision-Making. In Multiple Criteria Decision Analysis (pp. 363–419). Springer, New York, NY. https://doi.org/10.1007/978-1-4939-3094-4_10

1.3. AHP Methods Description

Aware of the Study 1 participant audience and their needs for information, I developed a methods description document to help explain the AHP methodological mechanics and justify the choice of model for people who needed that additional background. Based on post-survey responses, no one paid much attention to this document. In retrospect, it was clear to our researcher team that a separate document explaining methods was too much, and that participants should be able to understand DDST mechanics intuitively or easily navigate throughout the model to explore weighting, scoring, or ranking further.

Purpose

The purpose of building our own decision support tool is to tailor it to our needs for its use in a participatory decision-making workshop, while maintaining transparency for users. Excel was selected as the platform within which to build the tool because Excel is a commonly used data-entry program and will likely appear familiar to the workshop participants. Excel allows us to record and save participant responses for future reference. Developing our own model also allows us to create an online version to share with the public through the University of New Hampshire's Data Discovery Center website.



Decision problem hierarchy, with pairwise comparison processes depicted using directional arrows.

What is it?

The Analytical Hierarchy Process (AHP) is a type of Multi-Criteria Decision Analysis (MCDA) which expressly handles Decision Maker (DM) preferences. Key attributes of the AHP model include: a) hierarchical breakdown of the decision problem (image at left), b) pairwise comparisons of decision alternatives isolated on each criterion, c) pairwise comparisons of criteria against one another, and d) ranked results based solely on DM preferences. The theoretical context for this work is fuzzy set theory, Thomas Saaty (1990) saw a need to make DM judgments about preferences more consistent. For instance, it does not make sense to compare the decision of buying a car to selecting a snack to eat. Cars need to be compared with cars, the purchase of other motor vehicles, or large consumer purchases in general. Snacks, on the other hand, need to be compared with snacks, meals, food groups, or small purchases. These groupings of ‘like’ items (or items with some shared characteristic or attribute) make the decision easier for the DM, which is why in AHP we compare alternatives pairwise on each criterion, and then consider the criteria in isolation of the alternatives.

How does it work?

Let us begin the discussion of how it works by first describing the formal equation for the AHP. From the pairwise comparisons of *m* decision alternatives on *n* criteria, we can assemble a *consistent matrix* [*A*] (Eq.1) for each set of pairwise comparisons falling under a single criterion (i.e. one matrix for every criterion, plus one for the pure criteria vs. criteria comparison), where each value of the main diagonal is equal to unity, and every entry outside of the main diagonal has a reciprocal entry (e.g. $[a_1/a_2], [a_2/a_1]$). The reciprocal entries imply that the comparison of a_1 to a_2 is the inverse of the comparison of a_2 to a_1, which is critical to maintaining consistency:

$$[A] = \begin{bmatrix} a_1/a_1 & a_1/a_2 & \cdots & a_1/a_m \\ a_2/a_1 & a_2/a_2 & \ldots & a_2/a_m \\ \vdots & \vdots & \ddots & \vdots \\ a_m/a_1 & a_m/a_2 & \cdots & a_m/a_m \end{bmatrix} \tag{Eq.1}$$

Or, more familiarly:

$$[A] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1m} \\ a_{21} & 1 & \ldots & a_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & 1 \end{bmatrix} \tag{Eq.2}$$

where each entry *a* represents the DM rating for a pairwise comparison. Most equations skip this next computational step, but breaking it out helps highlight key differences from the WS method. The raw DM preference rating values are standardized by dividing the raw rating (e.g. a_{12}) by the column sum. This is called the *standardized matrix* $[A_s]$:

$$[A_s] = \begin{bmatrix} 1/\sum a_{m1} & a_{12}/\sum a_{m2} & \cdots & a_{1m}/\sum a_{mn} \\ a_{21}/\sum a_{m1} & 1/\sum a_{m2} & \dots & a_{2m}/\sum a_{mn} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1}/\sum a_{m1} & a_{m2}/\sum a_{m2} & \cdots & 1/\sum a_{mn} \end{bmatrix} \qquad \text{(Eq. 3)}$$

Standardized values from each standardized matrix are averaged by row using the geometric mean method,

$$\frac{\left[\left(\frac{1}{\sum a_{m1}}\right)+\left(\frac{a_{12}}{\sum a_{m2}}\right)\dots+\left(\frac{a_{1m}}{\sum a_{mn}}\right)\right]}{m} \rightarrow x_{11} \qquad \text{(Eq. 4)}$$

and repeated for each row of the standardized matrix *for every pairwise alternative matrix* (recall, there will be one for each criterion), resulting in a scalar local preference weight for each alternative under each criterion (this is equivalent to the "score" in WS MCDA):

$$\begin{bmatrix} x_{11} \\ x_{21} \\ \vdots \\ x_{m1} \end{bmatrix} \text{ and } \begin{bmatrix} x_{12} \\ x_{22} \\ \vdots \\ x_{m2} \end{bmatrix} \text{ …and } \begin{bmatrix} x_{1m} \\ x_{2m} \\ \vdots \\ x_{mn} \end{bmatrix} \rightarrow \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \dots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} = [X] \qquad \text{(Eq. 5)}$$

As mentioned earlier, the DM goes through the same process for the criteria, comparing criteria vs. criteria to form a consistent matrix [C]:

$$[C] = \begin{bmatrix} 1 & c_{12} & \cdots & c_{1n} \\ c_{21} & 1 & \dots & c_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1} & c_{n2} & \cdots & 1 \end{bmatrix} \qquad \text{(Eq. 6)}$$

dividing the raw rating (e.g. c_{12}) by the column sum to create a *standardized matrix*:

$$[C_s] = \begin{bmatrix} 1/\sum c_{n1} & c_{12}/\sum c_{n2} & \cdots & c_{1n}/\sum c_{\phi n} \\ c_{21}/\sum c_{n1} & 1/\sum c_{n2} & \dots & c_{2n}/\sum c_{\phi n} \\ \vdots & \vdots & \ddots & \vdots \\ c_{n1}/\sum c_{n1} & c_{n2}/\sum c_{n3} & \cdots & 1/\sum c_{\phi n} \end{bmatrix} \qquad \text{(Eq. 7)}$$

Averaging standardized values by row using the geometric mean method results in a vector of global preference weights (one weight for each criterion, equivalent to the "preference weight" in WS MCDA):

$$\frac{\left[\left(\frac{1}{\Sigma c_{n1}}\right)+\left(\frac{c_{12}}{\Sigma c_{n2}}\right)\ldots+\left(\frac{c_{1n}}{\Sigma c_{\phi n}}\right)\right]}{n} \;\Rightarrow\; w_1 \qquad \text{(Eq. 8)}$$

Together, these global weights make up the global weights vector, $\boldsymbol{W_G}$:

$$\begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix} = \boldsymbol{W}_G \qquad \text{(Eq. 9)}$$

Finally, the AHP uses weighted-sum methods to rank the decision alternatives based on decision maker preferences, similar to classic WS MCDA (for an example, see Klein and Whalley, 2015):

$$\boldsymbol{W_G} * \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1m} \\ y_{21} & y_{22} & \cdots & y_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ y_{m1} & y_{m2} & \cdots & y_{mn} \end{bmatrix} \qquad \text{(Eq. 10)}$$

$$\textstyle\sum_{m=1}^{n} y_{mn} = \begin{bmatrix} z_1 \\ z_2 \\ \vdots \\ z_m \end{bmatrix} \qquad \text{(Eq. 10)}$$

AHP differs from WS only in the *production* of the scores and weights. Realistically, the pairwise comparisons happen first, followed by the standardization, and then the weighted sum. Our model speeds up the process by performing the calculations as the DM enters the raw ratings in the consistency matrix. Our model also provides a simple, user-friendly interface with easy-to-follow directions, drop-down menus for rating selection, and supporting information to help the DM make choices.

Why are we using AHP instead of another MCDA model?

AHP is the most commonly used type of MCDA in natural resource management decision applications (Huang et al., 2011). You have seen some of the advantages to AHP in our discussion of what it is and how it works. Unlike other types of MCDA, AHP breaks down the decision problem into a series of smaller decisions within fuzzy sets (Saaty, 1990), a process which both groups 'like' factors and distances the DM from his or her gut feelings about the preferred solution. Some additional advantages to the AHP are: 1) allowance for inconsistency (up to 10%) in DM judgments; 2) transparency through use of weighted sum methods for the final decision alternative ranking calculation; and 3) flexibility in dealing with group preferences (can use averaged individual results or group deliberation). These three advantages are our motivating reasons for using AHP in a participatory workshop setting for dam decision making.

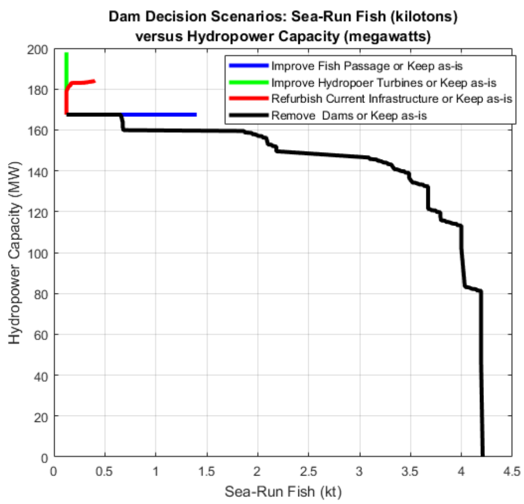
References

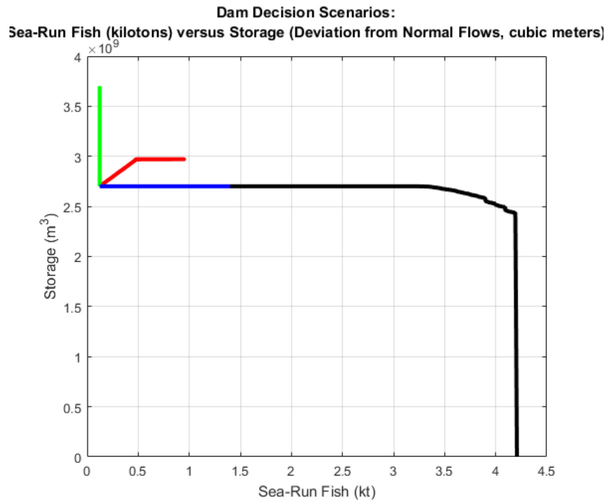
Huang, I. B., Keisler, J., Linkov, I. (2011). Multi-criteria decision analysis in environmental sciences: Ten years of applications and trends. *Science of the Total Environment*, 409: 3578-3594.

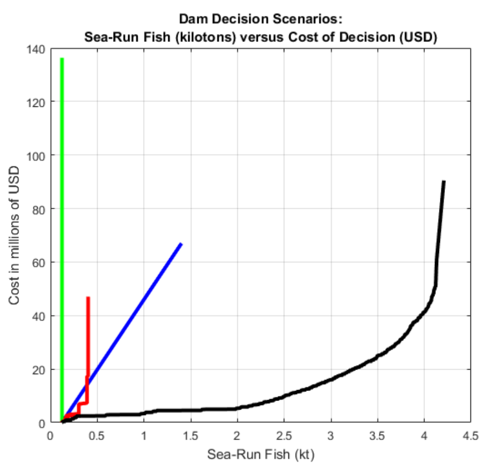
Saaty, T.L. (1990). How to make a decision: The Analytical Hierarchy Process. *European Journal of Operational Research*, *48*, 9-26.

1.4. Production Possibility Frontiers (PPFs)

The PPFs were part of the participant packet, aimed at supporting participant understanding of the tradeoffs involved in pairwise consideration of two decision alternatives under a single decision criterion.







2. Workshop 2: March 2019 UMaine Student Participant Packet

To streamline student participation, we excluded MCDA methodological background information, and limited the participant packet to the homework assignment, dam factsheets, and dam data tables. Note: students had access to each of these materials prior to the workshop. On the day of the workshop, student groups each received a color-printed copy of all dam factsheets and data tables. While Penobscot Mills Project was not a part of the decision scenario for this workshop, participants did see a factsheet and dam data table for the project overall, to provide some context for the section of the West Branch of the Penobscot River between Medway Dam and Ripogenus Dam.

2.1. Class Homework Assignment(s)

A Dam Decision Support Tool

Learning Objectives

(1) Understand complexities in hydropower decision making
(2) Understand basics of MCDA: Why use it? How?

Activities

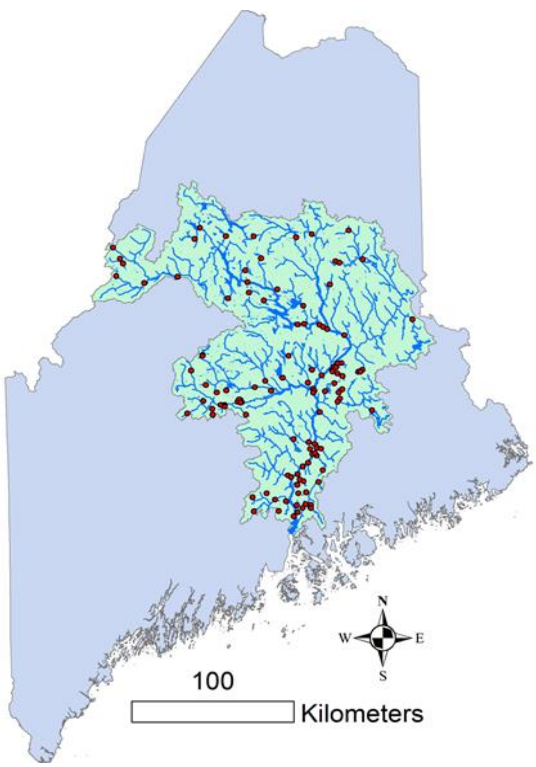
(1) Fill out pre-survey (HW due Feb 27)
(2) Test and critique Dam Toolbox

Homework Assignment (due 3/6): Individually test a web-based Dam Decision Support Tool. This Google Drive Folder holds all of the materials you will need for the assignment.

1. Please read the **Dam Toolbox Background** document and visit the Dam Decision Support Tool website.
2. You will need to run through the tool completely **FOUR TIMES** – one for each of the dams for which there are fact sheets (the same fact sheets and dams you considered for the pre-survey). Follow these instructions for EACH of these FOUR runs through the tool (one for each dam):
   a. **Start a timer**.
   b. READ the instructions on the "Start Here" page CAREFULLY (*you only have to read these instructions once*).
   c. Follow the instructions on the "Start Here" page to make decision criteria rating choices for each decision alternative for a specific dam site. Use the Dam Factsheet (see Google Drive folder) to help you.
   d. When you are finished making all of your decision criteria choices for all decision alternatives for the specific dam site, at the bottom of the Results page, **Download** the CSV file of your results and save it using the following format: **DAMSITE_LastNameFirstName_DATE**. For example: *MEDWAY_KleinSharon_2-27-19*.
   e. Take a **screenshot** of the final output on the Results page. Name the screenshot file with the following format: **DAMSITE_LastNameFirstName_DATE** (*For example: MEDWAY_KleinSharon_2-27-19*).
   f. **Stop the timer**. In cell M1 of your CSV file, enter the total time it took you to run through the tool AND download/take screenshots of the results. Save the CSV file.
   g. Repeat steps a-f for the other 2 dams. You should end up with 4 unique CSV files and 4 unique screenshots of your results. In cell N1 of your CSV file for Ripogenus, enter the TOTAL time it took you to run through the tool for all 4 dams.
   h. **Upload the 8 files** *(4 CSV and 4 screenshot files, all named properly)* to the proper folders within HW Assignment Files folder in the Google Drive folder linked above.
3. Take notes. Imagine that you are the professor, and you are grading the Decision Support Tool as a student's final project assignment. Are the instructions clear? Do the decision criteria make sense? Is the tool user friendly? Do you understand the results? Why or why not? What specific suggestions do you have for the student to improve the project? Save your notes as a Word or pdf document in the proper folder of HW Assignment Files in the Google Drive. Use the following name format for this notes file: LastNameFirstName_DATE (for example: KleinSharon_2-27-19).

2.2. Dam Toolbox Background

The Dam Toolbox was developed as part of the Participatory Multi-Criteria Decision Analysis (MCDA) Workshop. The Dam Decisions Support Tool, Dam Factsheets, and Multi-Criteria Decision Analysis with Multi-Objective Genetic Algorithm (MCDA-MOGA) model are components of this toolbox, a product collaboratively developed by researchers on the NSF-EPSCoR Future of Dams project.



Current dams in the Penobscot River watershed; image courtesy of Roy (2017).

Research Goal: We created this toolbox to support parties interested in participating in a Federal Energy Regulatory Commission (FERC) dam relicensing process; however, it is our hope that the Toolbox will be useful in other contexts as well. We envision the Toolbox supporting multiple decision makers (e.g., regulators, municipalities, or other legal participants in a FERC relicensing process) considering a diverse set of goals in a participatory setting (e.g., a regulatory agency working group or public meeting) to identify a shared set of priorities. We seek your input about how effective the Toolbox is in supporting decision processes, as well as how and when the Toolbox might be used in a FERC relicensing process to best support decision makers. Your participation and feedback will help us revise this Dam Toolbox to better support decision makers like you in future dam decisions.

Dam Toolbox Objectives: The Dam Toolbox builds on the work of Roy et al. (2018)[1] and is designed to: a) capture decision maker preference information about decision criteria (e.g., cost, fish mortality, hydropower generation, etc) and alternatives (e.g., remove dam, increase hydropower capacity, etc); b) rank potential decision alternatives based solely on user-defined preferences; c) refine rankings with location-specific decision criteria data; d) support multi-dam decision scenarios; and e) visually represent the user's decision output with a map.

The Dam Toolbox includes the following components, to be housed at the University of New Hampshire's Data Discovery Center after the workshop.

1) Dam Factsheets: a brief packet of information for each dam (3 documents total), including ownership history, site characteristics, and technical specifications, in addition to decision criteria performance data for all decision alternatives.
2) Dam Data Tables, with real baseline performance data for each decision alternative under every decision criterion, as well as qualitative indicators about how those performance data may change (increase or decrease) if a particular decision alternative is selected. Participants will also have access to Dam Data Tables during the workshop *only*.
3) Dam Decision Support Tool: an interactive web-based application to support user preference ratings for of a set of decision criteria under a series of decision alternatives.
4) Multi-Criteria Decision Analysis with Multi-Objective Genetic Algorithm (MCDA-MOGA): a hybrid MCDA model that calculates an optimum decision scenario (e.g., list of dams within a watershed to be removed, kept, etc.) based on an internal set of site-specific decision criteria performance values and user-defined preference values imported from the Dam Decision Support Tool.

The Dam Decision Support Tool provides a set of dam decision criteria and alternatives on which to base user preferences, the first step of an MCDA (a structured framework to help balance complex decisions). The tool asks the user to specify numeric preference values for each decision criterion under each decision alternative, where the sum of all preferences for any decision alternative must equal 1, so changes in one decision criterion preference value (e.g., increase preference for fish survival) must be compensated for by changes in another decision criterion preference value (e.g., decrease preference for hydropower generation). The results of the tool include: (a) a graph of decision alternatives for an individual dam broken down by decision criteria, based on user-defined preferences; (b) a graph of decision criteria for a single dam, broken down by decision alternative; and (c) a CSV file of the user preference ratings. Researchers feed these results into the MCDA-MOGA model, which generates an "efficient" combination of changes to a collection of dams in a given watershed, including removal of all dams and keeping and maintaining all dams (with a full spectrum of other options in between). The MCDA-MOGA model then applies the user-defined preference values to the potential decision alternatives for each dam in the multi-dam set (which may include a few dams or all dams in a watershed) and selects outcomes that maximize a total score (sum of normalized decision criteria values multiplied by user-defined preference weights) for each decision alternative for each dam. Researchers then map the coordinated, multi-dam outcome to produce a map which shows which dams from the original set remain in the watershed after the simulated decision.

We have compiled and defined a set of decision alternatives and decision criteria identified through interviews with decision makers and relevant to the Penobscot River watershed. The Dam Factsheets include site-specific data about the performance of each decision criterion under each decision alternative to help the user make choices in the Dam Decision Support Tool. The workshop will encourage users to make choices in the Tool in the context of a multi-dam decision. We are interested in exploring the benefits and drawbacks of coordinated, multi-dam decision making, given the potential advantages in efficiency and ecological restoration opportunities. This Dam Toolbox and the workshop focus on the Medway, West Enfield, and Ripogenus dams, which are all coming up for relicensing in the next 10 years. However, these tools can be modified to consider the entire Penobscot River Watershed and dams in other watersheds (subject to data availability). The decision-making activity and supporting tools are intended to be site-specific and data-driven for realism. ***See Dam Factsheets for Site-Specific Data***

Decision Alternatives

(1) Remove Dam: dam is removed completely from the river, allowing water to flow freely.

(2) Improve Fish Passage: some type of fish passage technology is installed (e.g., state-of-the-art fish lift/elevator, eel ladder, etc).

(3) Improve Hydropower Generation: (e.g., install turbines, upgrade turbines, or expand power capacity): hydropower generation capacity is increased, whether by installing new capacity or by upgrading turbines to larger power capacities or higher efficiency ratings; includes powered and non-powered dams.

(4) Improve Hydropower Generation AND Fish Passage: some type of fish passage technology is installed AND hydropower generation capacity is increased.

(5) Keep and Maintain Dam: this is the do-nothing option, where the dam remains in place and minimal costs are incurred to ensure dam structural integrity and safety compliance.

Decision Criteria

(1) Fish Survival (thousands of lbs or tonnes): proxy criteria estimated as sea-run fish (Atlantic salmon, Alewife, Blueback herring, American eel) biomass calculated using functional habitat units[1].

(2) River Recreation Area (square miles or kilometers): estimated area of river that may increase or decrease with a dam decision alternative, combines functional area for whitewater and flatwater recreation[1].

(3) Reservoir Storage (cubic miles or kilometers): estimated storage potential of the reservoir, based on its volume[1].

(4) Annuitized Project Costs (2018 $USD): estimated total project costs (capital and operation & maintenance) on an annual basis using a 6.2% discount rate and a 20 year lifetime.

(5) Number of Properties Impacted: estimated number of properties impacted by the decision alternative, based on potential changes in viewshed or property value[1].

(6) Breach Damage Potential (unitless): a proxy for safety based on the State hazard rating, which indicates the potential for downstream property damage, injury, and death in the case of dam breach.

(7) Annual Electricity Generation (MWh/yr): average estimate based on nameplate capacity from FERC licenses for each hydropower project.

(8) Annual CO_2 Emissions Reduction (lbs or tonnes of CO_2 per year): estimate of avoided carbon dioxide emissions from annual hydropower-generated electricity production; based on decreasing generation from the State's electricity generation mix; does not include life cycle emissions impacts.

(9) Indigenous Cultural Heritage (unitless): a proxy for the importance of the decision alternative for preserving/restoring the culture of indigenous people. Rating is calculated from a set of numeric values provided by decision makers answering a pre-survey.

(10) Town/City Identity (unitless): rating to convey the importance of the decision alternative for preserving the existing identity of the community of town/city residents. Rating is calculated from a set of numeric values provided by decision makers answering a pre-survey.

(11) Industrial Historical Importance (unitless): rating to convey the importance of the decision alternative for preserving/restoring the industrial historical value of the infrastructure. Rating is calculated from a set of numeric values provided by decision makers answering a pre-survey.

(12) Aesthetics (unitless): rating to convey the importance of the decision alternative for improving or preserving aesthetics (e.g., appearance, scenic value, smell, sound). Rating is calculated from a set of numeric values provided by decision makers answering a pre-survey.

References

[1]Roy, S.G., Uchida, E., de Souza, S.P., Blachly, B., Fox, E., Gardner, K., Gold, A.J., Jansujwicz, J., Klein, S., McGreavy, B., Mo, W., Smith, S.M.C., Vogler, E., Wilson, K., Zydlewski, J., & Hart, D. (2018). A multiscale approach to balance trade-offs among dam infrastructure, river restoration, and cost. *Proceedings of the National Academy of Sciences*, 201807437. doi:10.1073/pnas.1807437115.

[2]Roy, S.G. (2017). Damming Decisions: Searching for sustainable solutions in New England Rivers. Senator George J. Mitchell Center for Sustainability Solutions University of Maine. *Paper presentation.* Orono, ME.

[3]Kleinschmidt Associates (2015). *Maine Hydropower Study*. Commissioned for the Maine Governor's Energy Office.

[4]University of Maine Electrical and Computer Engineering. The Making of...Multimedia Power Systems Control and Simulation Labware. http://www.ewh.ieee.org/soc/es/Aug1996/008/cd/power/wenfield.htm

[5]West Enfield Dam (FERC No. 2600) license

[6]Low-Impact Hydropower Institute (2018). Map of existing low-impact certified dam structures. https://lowimpacthydro.org/project-map/.

[7]Ripogenus Dam (FERC No. 2572) license

[8]Great Northern Paper Company (2015). *Great Northern Paper Company Records, 1889 – 1992.* Raymond H. Fogler Library Special Collections Department. https://digitalcommons.library.umaine.edu/cgi/viewcontent.cgi?referer=&httpsredir=1&article=1264&context=findingaids

[9]Penobscot Mills Project (FERC No. 2458) license

[10]Rush, Jr., H.A.M. (2007). *Centennial Diary.* http://www.eastmillinocket.org/PHDInventory/documents/234479/234479_20527_984.pdf

[11]Medway Dam (FERC No. 2666) license

[12]Low Impact Hydropower Institute Certificate #65. https://lowimpacthydro.org/lihi-certificate-65-ferc-no-2666-medway-hydroelectric-project/

2.3. Factsheets

Factsheets had been developed separately, a project undertaken by undergraduate research assistant Kaitlyn Raffier, in an effort to compile information about dams in Maine into an easily accessed format that could be shared with stakeholders. This is an example factsheet from West Enfield Dam (later updated based on stakeholder feedback from member-checks).

West Enfield Dam

FERC No. 2600

Penobscot County, Howland and Enfield, ME

Dam owned by: Brookfield Renewables

Highlights[1,2]

- Installed and licensed in 1894
- Restructured 1988
- Single development situated between Howland and West Enfield, ME
- Privately owned
- Fish passage facility exists
- Not LIHI certified

Photo from Penobscot Nation website depicting the West Enfield Dam.

https://www.penobscotnation.org/departments/natural-resources/water-resources/dams

Ownership History[1&3]

1894: A rock-filled crib dam was constructed at this site.

1988: The original dam was replaced with this dam when Bangor-Pacific Hydro Associates redeveloped the entire project.

2014: Brookfield purchased dams and assumed West Enfield under the Penobscot Agreement.

Upcoming Decisions

- FERC Pre-application begins 2019
- FERC License expires May 31st, 2024

Drone shot of Penobscot River with dam on it.
https://www.fws.gov/news/ShowNews.cfm?ID=4F928157-CED5-9E63-1D41C23A5AC7707F

Technical specifics[4]

Dam dimensions: 980 ft long, 20 ft tall rock filled timber crib-dam

Turbines: 2 Bulb Propeller/Kaplan

Hydropower capacity: 13MW

Annual Electricity Generation: 73,200 MWh

Fish Passage Facilities: Vertical slot fishway for downstream passage, upstream eel ladder.

Operation schedule: typically operates 24 hrs/day. Operated as run-of-river, such that inflow equals outflow.

Additional Information: In the 2015 Maine Hydropower Study Kleinschmidt Associates estimate that the West Enfield Dam is outfitted with its maximum power capacity.

Stakeholders

Not a comprehensive list

1. Penobscot Indian Nation - *Sovereign Tribal Nation that depends on and uses the river.*
2. Brookfield Renewables– *Owner of the dam.*
3. Bangor-Pacific Hydro Associates
4. Federal Energy Regulation Commission (FERC) - *Responsible for granting hydropower operation licenses.*
5. U.S. Department of the Interior (DOI)
6. U.S. Department of Environmental Protection (DEP)
7. U.S. Fish and Wildlife Service (USFWS)
8. National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NOAA-NMFS)
9. Maine Department of Inland Fisheries and Wildlife (DIFW)
10. Maine Department of Marine Resources (DMR)
11. Maine State Planning Office
12. Town of Enfield - *Manages what happens within the boundaries of Enfield, ME.*
13. Town of Howland- *Manages what happens within the boundaries of Howland, ME.*
14. Penobscot River Restoration Trust- *Non-profit, no longer organized.*
    - American Rivers
    - Atlantic Salmon Federation
    - Maine Audubon
    - Natural Resource Council of Maine
    - Trout Unlimited

Topographic map of Penobscot River with West Enfield Dam on it.
http://www.mytopo.com/locations/index.cfm?fid=578134

Important Events[1,2]

1984: Previous relicensing.

1988: The dam was rebuilt from timber crib structure to concrete with hydropower capacity.

1980: Surface downstream fishway installed to provide passage around hydropower turbines.

Vertical Slot Fishway installed to provide upstream passage.

Important Media Coverage

- "Penobscot River Restoration Project Celebrates Final Milestone, Reconnects River to the Sea" by Judy Berk Posted on June 14, 2016 on NOAA.gov
  https://www.greateratlantic.fisheries.noaa.gov/mediacenter/2016/june/14_penobscot_river_restoration_project_celebrates_final_milestone__reconnects_river_to_the_sea.html
- "Six dams in Maine to be sold for $95 M" by Kevin Miller Posted on July 1, 2009 in the Bangor Daily News
  https://bangordailynews.com/2009/07/01/politics/six-dams-in-maine-to-be-sold-for-95m/?ref=relatedBox
- "Restoring the Penobscot" by Tom Bell Posted on September 18, 2011 in the Portland Press Herald
  http://www.pressherald.com/2011/09/18/pressherald_com_2011-09-18

DOWNSTREAM FISHWAY PIPE AT THE WEST ENFIELD PROJECT

file:///C:/Users/Katie/Downloads/20160216-5037(31238339)%20(1).pdf (From Sarah Vogel)[4]

References:

[1]Maine Hydro Plant Simulation Lab ware: WestEnfield Plant. (n.d.). Retrieved March 5, 2017, from http://www.ewh.ieee.org/soc/es/Aug1996/008/cd/power/wenfield.htm

[2]West Enfield License

[3]Penobscot River Restoration Trust. (n.d.). Fact Sheet 2016. Retrieved March 2, 2017, from http://www.penobscotriver.org/assets/2016PRRPfacts.pdf

[4]Sarah Vogel on Future of Dams Team

[5]Miller, K. (2009, July 1). Six dams in Maine to be sold for $95M. Retrieved March 8, 2017, from http://bangordailynews.com/2009/07/01/politics/six-dams-in-maine-to-be-sold-for-95m/

About the Authors:

This factsheet was created by:

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Faculty Advisor, Sharon Klein

Graduate Advisor, Emma Fox

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2.4. Dam Data Table Example

Dam Data Tables were developed to support student decision-making about dams. While the data tables were mostly qualitative (aside from the baseline current case data), the cells give an indication of how the decision criteria values could change under each possible decision alternative. This is an example data table for West Enfield.

Criteria performance under dam decision alternatives specific to the **West Enfield Dam** (+ =increase from baseline, **-** = decrease from baseline).

Decision Alternative	Sea-run fish survival (tonnes/year)	River recreation area (km^2)	Reser-voir storage (km^3)	Annuitized project costs ($2018 thousands)	Number properties impacted	Breach damage potential	Annual electricity generation (GWh/yr)	CO_2 Emissions reduction (kt/ yr)	Indigenous cultural heritage	Indus-trial histor-ical value	Town/City identity	Aesthetic value
BASELINE CASE	15	12	0	$950	5	2	73	14	2	3	3	2
Remove	+	+	-	+	-	+	-	-				
Improve Fish Passage	+	No change	No change	+	No change	No change	-	No change				
Improve Hydropower Generation	-	No change	No change	+	No change	No change	+	+				
Improve Hydropower AND Fish	-	No change	No change	+	No change	No change	+	+				
Keep and Maintain	No change	No change	No change	No change	No change	No change	No change	No change				

* Value averaged from student Pre-Survey results

3. Workshop 3: October 2019 Stakeholders

The participant packet for Study 3 was the most streamlined yet. We shared access to a Google Drive folder on the day of the workshop with Dam Factsheets, Dam Data Tables, and Decision Criteria/Alternative descriptions (all updated from Study 2).

3.1. Instructions For Dam Decision Support Participant Packet

Please do the following to prepare for the Dam Decision Support workshop:

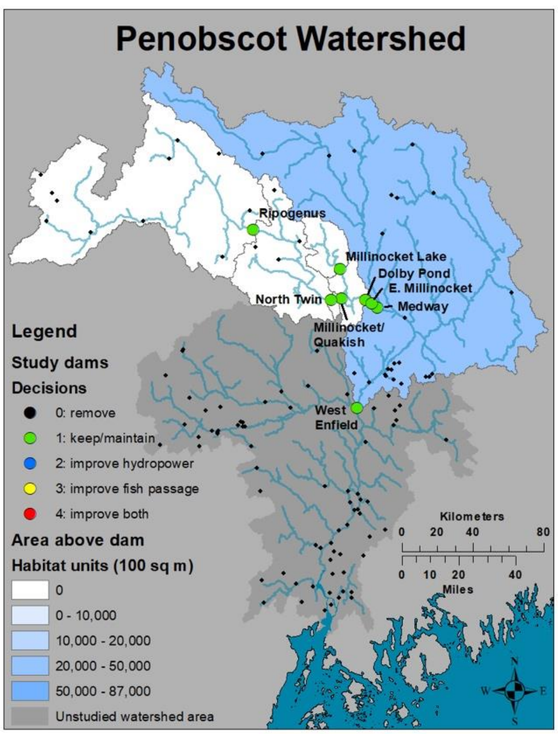
1. **Read** the Consent Form and Media Release Form that were emailed to you. You do not have to sign these now. Participating in the survey signifies consent, but you may exit at any time, or go back and edit your responses if you so choose. There will be a paper copy of the Consent Form available for you to sign at the workshop. Signing the Consent Form is required for participation in the Dam Decision Support Workshops. Signing the Media Release is not required for participation in these workshops but will allow us to use pictures we take of your participation in the workshops to help support us disseminating information about our research projects.
2. Fill out and submit the brief registration form for the workshop by **September 26, 2019**.
3. Find the set of documents in this Google Drive folder. It should be attached to the email with the survey participation link as well.
4. **Read** the following documents in the Google Drive folder in this order to understand the scope of the problem, decision criteria, decision alternatives, and specific information/data about each dam that we will be considering in the workshop:
    a. Background Dam Decision Support Tool
    b. Decision Alternatives Descriptions
    c. Decision Criteria Descriptions
    d. Four Dam Fact Sheets (West Enfield, Medway, Penobscot Mills, Ripogenus)
    e. Map Penobscot Watershed

   f. Decision Matrices (can be viewed in MS Excel or as a pdf; Excel version contains additional metadata information)

5. Click on the **pre-survey** link (sent via email) and answer as many questions as you have time for. The full survey could take up to an hour. If you do not have time for this, please prioritize the beginning section, **questions 1-9**, and the demographics at the end (**questions 58-62**) as you feel comfortable. If you have prior knowledge of any of the 8 dams we will be considering in the workshop or feel like you would like to answer questions about them based on the fact sheets, it would really help us out a lot if you could answer questions 10-57, but we understand not all participants will have time for these questions or may not feel comfortable answering them. So, if you need to skip these, that is ok. Please submit the pre-survey by 5pm on **Friday September 27, 2019**.

Thank you! We look forward to seeing you at the workshop! ☺

3.2. Background: Web-based Dam Decision Support Tool



Penobscot watershed dams up for relicensing within next decade

The Dam Decision Support Tool is a web app collaboratively developed by researchers on the NSF-EPSCoR Future of Dams project. The Tool was developed to be used in a Participatory Multi-Criteria Decision Analysis (MCDA) Workshop. The Dam Factsheets, information on Decision Alternatives and Decision Criteria, Decision Matrices, and Multi-Criteria Decision Analysis with Multi-Objective Genetic Algorithm (MCDA-MOGA) model are components of this Tool. ***Research Goal***

We created this tool to support parties interested in participating in or preparing for a Federal Energy

Regulatory Commission (FERC) dam relicensing process; however, it is our hope that the tool will be useful in other contexts as well. We envision the tool supporting a group of multiple decision makers with different interests (e.g., regulators, municipal officials, dam owners, non-governmental organization representatives, etc.) considering a diverse set of goals in a participatory setting (e.g., regulatory agency working group, public meeting, internal preparatory meeting, etc.) to identify a shared set of priorities. We seek your input about how effective the Dam Decision Support Tool is in supporting decision processes, as well as how and when the Tool might be used in or to prepare for a FERC relicensing process to best support decision makers. Your participation and feedback will help us revise this Tool to better support decision makers like you in future dam decisions.

Dam Decision Support Tool Objectives

The Dam Decision Support Tool builds on the work of Roy et al. (2018)[1] and is designed to: a) capture decision maker preference information about decision criteria (e.g., cost, fish mortality, hydropower generation, etc) and alternatives (e.g., remove dam, increase hydropower capacity, etc); b) rank potential decision alternatives based solely on user-defined preferences; c) refine rankings with location-specific decision criteria data; d) support multi-dam decision scenarios; and e) visually represent the user's decision output with a map.

The Dam Decision Support Tool includes the following components, to be housed at the University of New Hampshire's Data Discovery Center after the workshop.

1) Dam Factsheets: a brief packet of information for each FERC-licensed hydropower dam project (4 documents total), including ownership history, site characteristics, and technical specifications.
2) Dam Decision Matrices, with baseline performance data for each decision alternative under every decision criterion at each dam.
3) Multi-Criteria Decision Analysis (MCDA) with Multi-Objective Genetic Algorithm (MCDA-MOGA): an interactive web-based application to support user preference ratings for of a set of

decision criteria under a series of decision alternatives, pairing MCDA and MOGA. This is a hybrid MCDA model that calculates an optimum decision scenario (e.g., list of 8 dams within a watershed to be removed, kept, etc.) based on an internal set of site-specific decision criteria performance values and user-defined preference values elicited from the user.

The Dam Decision Support Tool provides a set of dam decision criteria and alternatives on which to base user preferences, the first step of an MCDA (a structured framework to help balance complex decisions). The tool asks the user to specify numeric preference values for each decision criterion at each individual dam site (8 total), where the sum of all preferences for any decision alternative must equal 1. Changes in one decision criterion preference value (e.g., increase preference for fish survival) must be compensated for by changes in another decision criterion preference value (e.g., decrease preference for hydropower generation). The MCDA-MOGA model generates an "efficient" combination of changes to a collection of dams in a given watershed, including removal of all dams and keeping and maintaining all dams (with a full spectrum of other options in between). The MOGA includes an algorithm that accounts for interaction between decision alternatives at individual dams for fish survival (i.e., fish survival at one dam depends on what happens at a dam upstream).

The MCDA-MOGA model then applies the user-defined preference values to the potential decision alternatives for each dam in the multi-dam set (which may include a few dams or all dams in a watershed) and selects outcomes that maximize a total score (sum of normalized decision criteria values multiplied by user-defined preference weights) for each decision alternative for each dam. The coordinated, multi-dam outcome is mapped to show which dams from the original set remain in the watershed after the simulated decision. The results of the tool include: (a) a graph of 'raw' user preference information for each dam; (b) a graph of decision alternatives for an individual dam broken down by decision criteria, based on user-defined preferences; (c) a graph of decision criteria for multiple dams, broken down by the top-ranked decision alternative; (d) a graph of the decision alternative rankings for all dams; (e) graphs of the final MCDA ranking for all dams with a map of the top-ranked multi-dam recommendation; (f) CSV downloads of the results.

We have compiled and defined a set of decision alternatives and decision criteria identified through interviews with decision makers and relevant to the set of 8 dams (4 hydropower projects) coming up for relicensing on the Penobscot River watershed. The Dam Decision Matrices include site-specific data about the performance of each decision criterion under each decision alternative to help the user make choices in the Dam Decision Support Tool. We are interested in exploring the benefits and drawbacks of single-dam decision making versus coordinated, multi-dam decision making, given the potential advantages with the latter in terms of efficiency and ecological restoration opportunities. This Dam Decision Support Tool and the workshop focus on the West Enfield[2], Medway[3], Millinocket[4], East Millinocket[4], North Twin[4], Dolby[4], Millinocket Lake[4], and Ripogenus[5] dams, which are all coming up for relicensing in the next 10 years. However, these tools can be modified to consider the entire Penobscot River Watershed and dams in other watersheds (subject to data availability)[1]. The decision-making activity and supporting tools are intended to be site-specific and data-driven for realism.

References

[1]Roy, S.G., Uchida, E., de Souza, S.P., Blachly, B., Fox, E., Gardner, K., Gold, A.J., Jansujwicz, J., Klein, S., McGreavy, B., Mo, W., Smith, S.M.C., Vogler, E., Wilson, K., Zydlewski, J., & Hart, D. (2018). A multiscale approach to balance trade-offs among dam infrastructure, river restoration, and cost. *Proceedings of the National Academy of Sciences*, 201807437. doi:10.1073/pnas.1807437115.

[2]West Enfield Dam (FERC No. 2600) license

[3]Medway Dam (FERC No. 2666) license

[4]Penobscot Mills Project (FERC No. 2458) license

[5]Ripogenus Dam (FERC No. 2572) license

3.3. Dam Factsheet Update for DDST 3

West Enfield Dam

FERC No. 2600

Penobscot County, Howland and Enfield, ME

Dam owned by: Brookfield Renewables

Highlights

- Stanford Dam constructed 1894, original license issued 1970
- Relicensed 1984, renamed "West Enfield Project"; restructured mid-late 1980s
- Single development situated between Howland and West Enfield, ME
- Privately owned
- Fish passage facility exists
- Not LIHI certified

https://www.penobscotnation.org/departments/natural-resources/water-resources/dams

Ownership History

1894: A rock-filled crib dam was constructed at this site.

1988: The original dam was replaced with this dam when Bangor-Pacific Hydro Associates redeveloped the entire project.[1]

1999: PPL Maine purchases asset as part of Maine's electric deregulation.

2009: PP: Maine sells asset to Black Bear Hydro Partners, LLC, an affiliate of ArcLight Capital Partners, LLC

2014: Brookfield purchased asset. West Enfield included in the Lower Penobscot River Settlement Accord.[4] As a part of the Accord, FERC authorizes a 1-foot increase in the headpond to increase generation.

Upcoming Decisions

- FERC Pre-Application Document (PAD) filed May 31st, 2019
- FERC site visit and scoping meeting to be held August 2019
- Current FERC License expires May 31st, 2024

https://farm3.staticflickr.com/2717/4041591062_82a9e74080_b.jpg

Technical specifics[2]

Dam dimensions: 39-feet-high consisting of a 194-foot-long non-overflow spillway, a 107-foot-long gated spillway, and a 363-foot-long overflow spillway surmounted with 7-foot-high flashboards

Turbines: 2 horizontal Kaplan pit turbines

Hydropower capacity: 13MW

Annual Electricity Generation: 91,763 MWh (2014- 2018)

Fish Passage Facilities: Vertical slot fishway for upstream passage, downstream fish passage is five 4-ft x 14ft high surface bypass entrances. Eel passage is separate eel ladder.

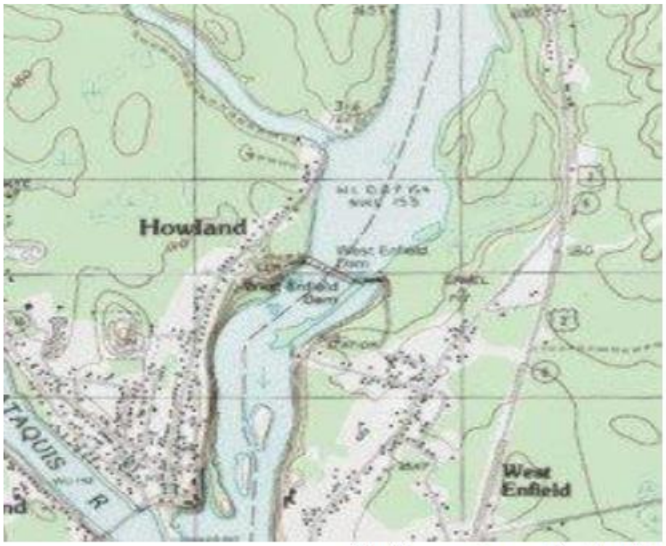
Operation schedule: typically operates 24 hrs/day. Operated as run-of-river, such that inflow equals outflow.

Additional Information: In the 2015 Maine Hydropower Study Kleinschmidt Associates estimate that the West Enfield Dam is outfitted with its maximum power capacity.

Stakeholders

Not a comprehensive list

1. Brookfield Renewable– *Owner of the dam.*
2. Bangor-Pacific Hydro Associates – *Subsidiary of Brookfield Renewable, the owner and operator of the dam.*
3. Penobscot Nation - *Sovereign Tribal Nation that depends on and uses the river.*
4. Town of Enfield - *Manages what happens within the boundaries of Enfield, ME.*
5. Town of Howland- *Manages what happens within the boundaries of Howland, ME.*
6. Bureau of Indian Affairs (BIA)
7. National Park Service (NPS)
8. Department of Environmental Protection (DEP)
9. National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NOAA-NMFS)
10. U.S. Fish and Wildlife Service (USFWS)
11. Maine Department of Inland Fisheries and Wildlife (DIFW)
12. Maine Department of Marine Resources (DMR)
13. American Rivers
14. Maine Rivers
15. Conservation Law Foundation
16. Atlantic Salmon Federation
17. Maine Audubon
18. The Nature Conservancy
19. Natural Resource Council of Maine
20. Trout Unlimited



http://www.mytopo.com/locations/index.cfm?fid=578134

Past Media Coverage

- "Penobscot River Restoration Project Celebrates Final Milestone, Reconnects River to the Sea" by Judy Berk Posted on June 14, 2016 on NOAA.gov https://www.greateratlantic.fisheries.noaa.gov/mediacenter/2016/june/14_penobscot_river_restoration_project_celebrates_final_milestone__reconnects_river_to_the_sea.html
- "Six dams in Maine to be sold for $95 M" by Kevin Miller Posted on July 1, 2009 in the Bangor Daily News https://bangordailynews.com/2009/07/01/politics/six-dams-in-maine-to-be-sold-for-95m/?ref=relatedBox
- "Restoring the Penobscot" by Tom Bell Posted on September 18, 2011 in the Portland Press Herald http://www.pressherald.com/2011/09/18/pressherald_com_2011-09-18

Important Events

1984: Previous relicensing.

1988: The dam was rebuilt from timber crib structure to concrete with hydropower capacity.

1980: Surface downstream fishway installed to provide passage around hydropower turbines.

2004: Lower Penobscot River Settlement Accord. Vertical slot fishway installed to provide upstream passage.

DOWNSTREAM FISHWAY PIPE AT THE WEST ENFIELD PROJECT

file:///C:/Users/Katie/Downloads/20160216-5037(31238339)%20(1).pdf (From Sarah Vogel)

References:

[1]Maine Hydro Plant Simulation Lab ware: WestEnfield Plant. (n.d.). Retrieved March 5, 2017, from http://www.ewh.ieee.org/soc/es/Aug1996/008/cd/power/wenfield.htm

[2]Sarah Vogel on Future of Dams Team

[3]Miller, K. (2009, July 1). Six dams in Maine to be sold for $95M. Retrieved March 8, 2017, from http://bangordailynews.com/2009/07/01/politics/six-dams-in-maine-to-be-sold-for-95m/

[4]Penobscot River Restoration Trust. (n.d.). Fact Sheet 2016. Retrieved March 2, 2017, from http://www.penobscotriver.org/assets/2016PRRPfacts.pdf

org/assets/2016PRRPfacts.pdf

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3.4. Decision Criteria and Alternative Descriptions

Decision Criteria

1. **Sea-run fish habitat area** (hundreds of square meters): proxy criteria estimated as possible upstream sea-run fish (Atlantic salmon, Alewife, Blueback herring, American eel) functional habitat area (Roy et al., 2018).
2. **River recreation area** (square kilometers): estimated downstream area of river that may increase or decrease with a dam decision alternative, represents functional area for whitewater recreation defined by Roy et al. (2018).
3. **Reservoir storage** (100,000 acre-feet): estimated storage potential of the reservoir, based on its volume (Roy et al., 2018).
4. **Annuitized project costs** ($2018 thousands USD/yr): estimated total project costs (capital and operation & maintenance) on an annual basis using a 6.2% discount rate and a 20 year lifetime.
5. **Number of properties impacted**: estimated number of properties impacted by the decision alternative, based on potential changes in viewshed or property value (Roy et al., 2018).
6. **Breach damage potential** (unitless): a proxy for safety based on the State hazard rating, which indicates the potential for downstream property damage, injury, and death in the case of dam breach (Roy et al., 2018).
7. **Annual electricity generation** (GWh/yr): average estimate based on nameplate capacity from FERC licenses for each hydropower project.
8. **Annual carbon dioxide (CO2) emissions reduction** (metric kilotonnes per year): estimate of avoided carbon dioxide emissions from annual hydropower-generated electricity production (reservoir or diversion-design dams); based on decreasing generation from the State's electricity generation mix; includes life cycle emissions impacts.
9. **Indigenous cultural traditions and lifeways** (unitless): rating to convey the importance of the dam for preserving/restoring the culture and practices of indigenous people.

10. **Community identity** (unitless): rating to convey the importance of the dam for preserving the existing community identity for residents living along or on islands within the river.
11. **Industrial historical importance** (unitless): rating to convey the importance of the dam for preserving/restoring the industrial history of the site.
12. **Aesthetic value** (unitless): rating to convey the importance of improving or preserving aesthetics (e.g., appearance, scenic value, smell, sound).
13. **Public health** (unitless): rating to convey the importance of public health, which is connected to air, water, and land pollution.
14. **Socio-environmental justice** (unitless): rating to convey the importance of socio-environmental justice issues (e.g., negative environmental effects that target disadvantaged groups – people of lower socio-economic status or with less political or economic power).

Decision Alternatives

1. **Remove dam:** dam is removed completely from the river, allowing water to flow freely
2. **Improve fish passage:** some type of fish passage structure is installed (e.g., state-of-the-art fish lift/elevator, eel ladder, etc).
3. **Improve hydropower generation:** hydropower generation capacity is increased by installing new capacity or by upgrading turbines to larger power capacities or higher efficiency ratings; includes powered and non-powered dams.
4. **Improve hydropower generation AND fish passage:** some type of fish passage structure is installed AND hydropower generation capacity is increased.
5. **Keep and maintain dam:** this is the business-as-usual option, where the dam remains in place and minimal costs are incurred to ensure dam structural integrity and safety compliance.

Removal: When a dam is removed, water is allowed to flow more freely downstream, creating greater connectivity for fish passage and river recreation, bolstering sea-run fish populations, and improving benthic (riverbed) aquatic communities. Dam removal may improve local water quality, regulate water temperature, and provide additional tourism/fishing opportunities. The river will likely return to its "natural" flow. However, dam removal may also create temporary mud flats as the reservoir empties, and/or release toxic or harmful impounded sediments. Dam removal eliminates lake-dwelling wildlife habitat and local flatwater recreation opportunities, reduces overall reservoir storage volume, and eliminates hydropower generation at the dam. Near-term costs are typically high for dam removals, with no direct market returns. Outside funding may exist for this decision alternative.

Improve Fish Passage: Improvements to a dam's fish passage may increase survival for one or more sea-run fish species within the watershed and improve angling in the river. Improvements to fish passage may even provide learning opportunities for citizens and students. However, annual electricity generation may be diminished (depending on the technology selected to pass fish), and fish passage costs are typically high. Fish passage improvements may be required by law depending on the species migrating in the waterway, and additional improvements may become required as other species become threatened or endangered. In the case where the owner is required to improve passage for sea-run fish species, the owners must bear the high cost or risk surrendering the dam operation license. In some cases, agencies may be able to help offset costs.

Improve Hydropower Generation: When new turbines are installed on existing non-powered dams, or hydropower capacity is increased at a powered dam, annual hydropower generation increases. Similarly, upgrading or replacing turbines may increase annual generation and improve longevity for a hydropower dam. Increases in hydropower generation may reduce greenhouse gas emissions that contribute to climate change. Costs, borne by the dam owner, are high, but may be recouped through market returns over the project's lifetime. Change in the dam's operation may even present opportunities for whitewater recreation downstream (dam releases are popular for river rafting). However, installing turbines or expanding existing power capacity may alter flows and confuse sea-run fish species.

Fish may become caught in the grates protecting system intakes, or even be killed by turbine blades or rapid changes in pressure if they are small enough to move through the powerhouse. Actual reservoir storage may change based on overall hydropower operations.

Improve Hydropower Generation AND Fish Passage: When hydropower generation improvements AND fish passage improvements are made to a dam (powered or non-powered), they may increase survival for sea-run fish species within the watershed. This decision alternative may improve angling in the river. However, installing turbines or expanding existing power capacity may also alter flows and confuse sea-run fish species, who may be attracted to the water moving through the system intake. Fish may become caught in the grates protecting the system intake, or even killed by turbine blades or rapid changes in pressure if they are small enough to move through the powerhouse. Costs are typically high and borne by the owner. Annual electricity generation will increase overall, and revenue may help recoup costs over the project's lifetime. Increases in hydropower generation may reduce greenhouse gas emissions that contribute to climate change. Turbine operation may be less efficient with fish passage (depending on the technology selected), and fish passage costs are typically high. Fish passage may be required by law depending on the species migrating in the waterway, and additional improvements may become required as other species become threatened or endangered.

Keep and Maintain Dam: Keeping and maintaining the dam is generally the lowest-cost option in the near-term, with only the bare minimum updates to the dam for safety. Keeping and maintaining the dam may appeal to parties interested in preserving the area's industrial history, preserving the community identity for local residents (if community identity is closely tied to the dam), or preserving the aesthetic value of the impoundment. Maintenance costs may be recouped somewhat if the dam is powered; however, refurbishment, restoration, or maintenance to a non-powered dam presents no direct opportunity for cost offset. Keeping the dam will likely have no impact on reservoir storage volume, river recreation area, annual electricity generation, or number of properties abutting the reservoir. The impoundment will continue to present a barrier to sea-run fish species, thereby negatively impacting their survival.

3.5. Dam Data Table Example

West Enfield Dam FERC No. P-2600 : RAW DECISION MATRIX (cell values are data values and have not been changed in any way)

Decision Criteria	Keep and Maintain Dam	Improve Fish Passage	Improve Hydropower Capacity	Improve Hydro AND Fish Passage	Remove Dam
Sea-run fish habitat area (100 square m)	24,200	55,480	24,200	55,480	86,750
River recreation area (square km)	12	12	12	12	12-26
Reservoir storage (100,000 acre feet)	0	0	0	0	0
Annuitized project costs ($2018 thousands/yr)	949	1,067	949	1,067	179
Breach Damage Potential	3	3	3	3	0
Number of Properties Impacted	0	0	0	0	5
Annual Electricity Generation (GWh/yr)*	73	73	73	73	0
CO_2 Emissions Reduction (kilotonne/yr)	10	10	10	10	0
Indigenous Lifeways					
Industrial Historical Value					
Community Identity					
Aesthetic Value					
Public Health					
Social and Environmental Justice					

*1 GWh = 1000 MWh, so to convert from GWh to MWh, multiply the value by 1,000. To convert from MWh to GWh, divide by 1,000.

APPENDIX L: SURVEY INSTRUMENTS

All surveys were implemented in Google Forms.

1. Study 1 Pre-/Post-Survey

PRE-SURVEY FUTURE OF DAMS WORKSHOP

The primary purpose of this assessment is to help us evaluate the Mock Workshop and gather feedback to improve our design for the stakeholder workshop in Fall 2018.

Email Address:______________________

In your opinion, what is the **single** most important aspect of a dam and its reservoir? List only one.

In your opinion, what is the **single** most important aspect of a free-flowing river? List only one.

What are the **three** most common arguments you encounter to keep a dam? List three.

What are the **three** most common arguments you encounter to remove a dam? List three.

Which of the following do you think is a good use of tax dollars? Check all that apply.

- Removal of a **non-powered** dam is a good use of tax dollars. Yes/No/I don't know
- Removal of a **powered** dam is a good use of tax dollars. Yes/No/I don't know
- Repair or maintenance to a **non-powered** dam is a good use of tax dollars. Yes/No/I don't know
- Repair or maintenance to a **powered** dam is a good use of tax dollars. Yes/No/I don't know
- Fish passage facility improvements to an existing **powered** dam is a good use of tax dollars. Yes/No/I don't know
- Fish passage facility improvements to an existing **non-powered** dam is a good use of tax dollars. Yes/No/I don't know
- Turbine or other electromechanical equipment improvements to an existing **powered** dam is a good use of tax dollars. Yes/No/I don't know
- *No spending on infrastructure improvement* is a good use of tax dollars. Yes/No/I don't know

Please rate each of the following criteria relating to dams in terms of their importance.

	Not Important	Somewhat Unimportant	Neither important nor unimportant	Somewhat Important	Extremely Important
Cultural heritage					
Historical importance					
Aesthetics					
Fish passage					
Ecosystem Health					
Water quality					
Reservoir storage					
Safety					
Invasive species					
Property value					
Recreation opportunities					
Job creation					
Electricity generation					
Flood control					
Changes in natural flows					
Changes in sediment transport					
Water quality					
Reservoir water levels					
Costs of production, operation, maintenance					

	Not Important	Somewhat Unimportant	Neither important nor unimportant	Somewhat Important	Extremely Important
Changes in river or stream access					
Capital cost (e.g., upfront cost)					
Revenue					
Economic development					
Endangered species					
Fish survival					
Climate change					
Land use					
Sediment buildup					
Avoided air pollution					
Energy security					
Reliable, on-demand electrical grid support					
Erosion					

Are there any criteria we missed? Let us know!

Did you look at the (optional) supplementary material folder?

- ○ Yes
- ○ No
- ○ What supplementary material?

Questions, comments, suggestions?

POST-SURVEY FUTURE OF DAMS WORKSHOP

The purpose of this survey is to help us evaluate the Mock Workshop and gather feedback to improve the design of our stakeholder workshops planned for Fall 2018.

Email address: ___________________________

Which of the following do you think is a good use of tax dollars? Check all that apply.

1 Removal of a **non-powered** dam is a good use of tax dollars. Yes/No/I don't know

2 Removal of a **powered** dam is a good use of tax dollars. Yes/No

3 Repair or maintenance to a **non-powered** dam is a good use of tax dollars. Yes/No/I don't know

4 Repair or maintenance to a **powered** dam is a good use of tax dollars. Yes/No/I don't know

5 Fish passage facility improvements to an existing **powered** dam is a good use of tax dollars. Yes/No/I don't know

6 Fish passage facility improvements to an existing **non-powered** dam is a good use of tax dollars. Yes/No/I don't know

7 Turbine or other electromechanical equipment improvements to an existing **powered** dam is a good use of tax dollars. Yes/No/I don't know

8 *No spending on infrastructure improvement* is a good use of tax dollars. Yes/No/I don't know

Please rate each of the following criteria relating to dams in terms of their importance.

	Not Important	Somewhat Unimportant	Neither important nor unimportant	Somewhat Important	Extremely Important
Cultural heritage					
Historical importance					
Aesthetics					
Fish passage					
Ecosystem Health					
Water quality					
Reservoir storage					
Safety					
Invasive species					

	Not Important	Somewhat Unimportant	Neither important nor unimportant	Somewhat Important	Extremely Important
Property value					
Recreation opportunities					
Job creation					
Electricity generation					
Flood control					
Changes in natural flows					
Changes in sediment transport					
Water quality					
Reservoir water levels					
Costs of production, operation, maintenance					
Changes in river or stream access					
Capital cost (e.g., upfront cost)					
Revenue					
Economic development					
Endangered species					
Fish survival					
Climate change					
Land use					
Sediment buildup					

	Not Important	Somewhat Unimportant	Neither important nor unimportant	Somewhat Important	Extremely Important
Avoided air pollution					
Energy security					
Reliable, on-demand electrical grid support					
Erosion					

How much did you like/dislike the workshop activity? Please rate the following:

	N/A	Disliked a lot	Somewhat disliked	Neither liked nor disliked	Somewhat liked	Liked a lot
Overall experience						
Group negotiation						
Watershed maps						
PPF diagrams						
Results presentation						
Facilitation style						
Instruction (in beginning)						
Decision scenario						
Preparation material						
Excel-based Decision Tool						
Discussion/Debrief						

How much did you learn from the workshop activity? Please rate the following:

	N/A	Did not learn anything	Learned a little	Learned some	Learned a lot
Overall experience					
Group negotiation					
Watershed maps					
PPF diagrams					
Results presentation					
Facilitation style					
Results presentation					
Decision scenario					
Instruction (in beginning)					
Decision scenario					
Preparation material					
Excel-based Decision Tool					
Discussion/Debrief					

Evaluation of this activity by participants is critical to our development of useful decision tools. Please rate the following.

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
The negotiation was manageable					
The negotiation was useful to me					

The group negotiation was successful					
Consensus was reached					
The outcome is useful					
The outcome is equitable					
The outcome is environmentally sustainable					
The outcome is socially sustainable					
The outcome is economically sustainable					
The outcome is technically sustainable					
The workshop facilitated trust-building					
The workshop was transparent					
The guidance/facilitation was adaptive					
The process was accessible; it made sense					
The workshop enhanced my capacity for decision making					
I would use a similar process in my own decision making					

Are there any other questions you think we should be asking in the pre- and post-survey? Please list here.

Please discuss anything in particular you learned from the workshop or anything you found interesting.

Please discuss any particular challenges or difficulties you encountered in the workshop.

Please discuss any suggestions for improvement you have for future workshops like this.

Suggestions, questions, comments?

2. Study 2 Pre-/Post-Survey

PRE-SURVEY FOR STUDENT WORKSHOP

Thank you for agreeing to fill out this survey. The purpose of this survey is to collect individual participant preference information prior to a Dam Decision Support Workshop. Your answers will help inform the assessment of the decision support tools designed for participatory use in the workshop.

Email address:_________________

First Name:___________________

Last Name:___________________

Section 1: Dams and Rivers

(1) In your opinion, what is the SINGLE most important aspect of a dam and its reservoir? (List only one)

(2) In your opinion, what is the SINGLE most important aspect of a free-flowing river? (List only one)

(3) What are the THREE most common arguments you encounter to keep a dam? (List three)

(4) What are the THREE most common arguments you encounter to remove a dam? (List three)

Section 2: Dam Decision Alternatives

(5) To what extent do you prefer the following decision alternatives? Check one for every row.

	Strongly *do not* prefer	Do *not* prefer	Neutral	Prefer	Strongly prefer
Removal of a **non-powered** dam.					
Removal of a **powered** dam.					
Repair or maintenance to a **non-powered** dam					
Repair or maintenance to a **powered** dam.					
Fish passage improvements at a **powered** dam.					
Fish passage improvements at a **non-powered** dam.					
Turbine or other electromechanical equipment improvements at a **powered** dam.					

	Strongly *do not* prefer	Do *not* prefer	Neutral	Prefer	Strongly prefer
Turbine installation (power capacity expansion) at a **non-powered** dam.					
Turbine or other electromechanical equipment improvements *and* fish passage improvements at a **powered** dam.					
Turbine installation (power capacity expansion) *and* fish passage improvements at a **non-powered** dam.					

Section 3: Issues Related to Dams

(6) How important do you consider each of the following issues related to dams. Check one for every row.

	Not Important	Somewhat Unimportant	Neither important nor unimportant	Somewhat Important	Important
Indigenous cultural heritage					
Industrial historical importance					
Aesthetics					
Town/City Identity					
Fish survival					
Ecosystem Health					
Water quality					
Reservoir storage					
Breach hazard potential					
Invasive species					
Number of properties impacted					
River recreation area					
Employment					
Annual electricity generation					

	Not Important	Somewhat Unimportant	Neither important nor unimportant	Somewhat Important	Important
Flood control					
Changes in natural flows					
Changes in sediment transport					
Changes in reservoir water levels					
Annuitized project costs					
Economic development					
Endangered species					
Climate change					
Changes in land use					
Annual CO2 emissions avoided					
Erosion					

(7) Are there any **issues** that we missed? List them here.

Section 4: Penobscot River Dams*

In this part of the survey, you will be asked to consider several dam projects coming up for Federal Energy Regulatory Commission (FERC) relicensing in the Penobscot River Watershed: Medway Dam, Ripogenus Dam, West Enfield Dam, and Penobscot Mills Project (also referred to as Great Northern Paper Mill). During any relicensing process, the hydropower operation license application is opened to public comment, water quality certifications are issued, and federal and state agencies alike submit formal opinions about the operation of the dam.

For each of the questions here, you will rate a series of decision criteria (attributes), specific to a list of decision alternatives (possible options) for a specific dam. It is important to consider each decision criterion only in terms of the corresponding decision alternative specific to the dam project (e.g. If the following decision alternatives happen, how do you rate the protection or preservation of INDUSTRIAL HISTORICAL IMPORTANCE at the MEDWAY DAM?). The questions appear repetitive, but they are each linked to a specific decision alternative for a specific dam, so please consider carefully. You may use the Dam Factsheets to inform your choices.

**NOTE TO THE READER: The following Medway Dam-specific questions are representative of the set of questions that the participants will encounter in sections 5 – 7, for each of the other 3 hydropower projects identified in section 4 (West Enfield Dam, Ripogenus Dam, and the Penobscot Mills Project). Participants may skip answering about dams with which they are not familiar.*

In each of these dam sections, participants are asked about six decision criteria: aesthetics, community identity, indigenous cultural traditions and lifeways, industrial historical importance, public health, and socio-environmental justice. Participants are asked to consider the same set of 5 decision alternatives

(Remove Dam, Improve Fish Passage, Improve Hydropower Generation, Improve BOTH Fish AND Hydro, and Keep and Maintain) for each decision criterion.

MEDWAY DAM

(8) If the following decision alternatives happen, how do you rate the protection or preservation of AESTHETICS at the MEDWAY DAM? Check one box per row.

Decision Criterion 1: AESTHETICS - rating to convey the importance of the decision alternative for improving or preserving aesthetics (e.g., appearance, scenic value, smell, sound).	**1= No protections**	**2**	**3**	**4**	**5= Strong protections**
Keep and Maintain Dam: this is the do-nothing option, where the dam remains in place and minimal costs are incurred to ensure dam structural integrity and safety compliance.					
Remove Dam: dam is removed completely from the river, allowing water to flow freely.					
Improve Hydropower Generation: Hydropower generation capacity is increased, whether by installing new capacity or by upgrading turbines to larger power capacities or higher efficiency ratings; includes powered and non-powered dams.					
Improve Fish Passage: some type of fish passage technology is installed (e.g., state-of-the-art fish lift/elevator, eel ladder, etc).					
Improve Fish Passage AND Hydropower Generation: some type of fish passage technology is installed AND hydropower generation capacity is increased.					

(9) If the following decision alternatives happen, how do you rate the protection or preservation of TOWN/CITY IDENTITY at the MEDWAY DAM? Check one box per row.

Decision Criterion 2: TOWN/CITY IDENTITY - rating to convey the importance of the decision alternative for preserving the existing identity of the community of town/city residents.	**1= No protections**	**2**	**3**	**4**	**5= Strong protections**

Keep and Maintain Dam: this is the do-nothing option, where the dam remains in place and minimal costs are incurred to ensure dam structural integrity and safety compliance.					
Remove Dam: dam is removed completely from the river, allowing water to flow freely.					
Improve Hydropower Generation: Hydropower generation capacity is increased, whether by installing new capacity or by upgrading turbines to larger power capacities or higher efficiency ratings; includes powered and non-powered dams.					
Improve Fish Passage: some type of fish passage technology is installed (e.g., state-of-the-art fish lift/elevator, eel ladder, etc).					
Improve Fish Passage AND Hydropower Generation: some type of fish passage technology is installed AND hydropower generation capacity is increased.					

(10) If the following decision alternatives happen, how do you rate the protection or preservation of INDIGENOUS CULTURAL HERITAGE at the MEDWAY DAM? <u>Check one box per row.</u>

Decision Criterion 3: INDIGENOUS CULTURAL HERITAGE - a proxy for the importance of the decision alternative for preserving/restoring the culture of indigenous people.	**1= No protections**	**2**	**3**	**4**	**5= Strong protections**
Keep and Maintain Dam: this is the do-nothing option, where the dam remains in place and minimal costs are incurred to ensure dam structural integrity and safety compliance.					
Remove Dam: dam is removed completely from the river, allowing water to flow freely.					
Improve Hydropower Generation: Hydropower generation capacity is increased, whether by installing new capacity or by upgrading turbines to larger power capacities or higher efficiency ratings;					

includes powered and non-powered dams.					
Improve Fish Passage: some type of fish passage technology is installed (e.g., state-of-the-art fish lift/elevator, eel ladder, etc).					
Improve Fish Passage AND Hydropower Generation: some type of fish passage technology is installed AND hydropower generation capacity is increased.					

(11) If the following decision alternatives happen, how do you rate the protection or preservation of INDUSTRIAL HISTORICAL IMPORTANCE at the MEDWAY DAM? <u>Check one box per row.</u>

Decision Criterion 4: INDUSTRIAL HISTORICAL IMPORTANCE - A rating to convey the importance of the decision alternative for preserving/restoring the industrial historical value of the infrastructure.	**1= No protections**	**2**	**3**	**4**	**5= Strong protections**
Keep and Maintain Dam: this is the do-nothing option, where the dam remains in place and minimal costs are incurred to ensure dam structural integrity and safety compliance.					
Remove Dam: dam is removed completely from the river, allowing water to flow freely.					
Improve Hydropower Generation: Hydropower generation capacity is increased, whether by installing new capacity or by upgrading turbines to larger power capacities or higher efficiency ratings; includes powered and non-powered dams.					
Improve Fish Passage: some type of fish passage technology is installed (e.g., state-of-the-art fish lift/elevator, eel ladder, etc).					
Improve Fish Passage AND Hydropower Generation: some type of fish passage technology is installed AND hydropower generation capacity is increased.					

Section 5: Demographics

This final section of the survey includes a standard set of demographic questions to help us analyze survey responses. All data will be kept confidential. You may skip any question.

(24) How many years have you been working with rivers/dams?

1. Under 1 year
2. 1 – 2 years
3. 3 – 5 years
4. 6 – 10 years
5. 11 – 15 years
6. 16 – 20 years
7. More than 20 years

(25) How old are you? (Drop-down selection)

1. Under 20 years
2. 21 – 25 years
3. 26 – 30 years
4. 31 – 35 years
5. 36 – 40 years
6. 41 – 45 years
7. 46 – 50 years
8. 51 – 55 years
9. 56 – 60 years
10. 61 – 65 years
11. 66 – 70 years
12. Over 70 years

(26) What is your gender? (Select one)

___Male

___Female

___Non-conforming/non-binary/third gender

___Prefer not to say

___Other:

(27) What is the highest level of education you have completed? (Select one)

__Some high school

__High school graduate or GED

__Some college or Associate's degree

__College Graduate (Bachelor degree or equivalent)

__Postgraduate (Master's, Doctorate, Law or other degree)

(28) Which of the following represents your current employment status? (Select all that apply)

__Student

__Employed full-time

__Employed part-time

__Flexible employment/contract employment

__Homemaker

__Unemployed

__Retired (not working)

___ Other (please specify):____

Thank you for your responses!

Thank you for filling out the pre-survey. Your responses will help us to create a workshop experience that better captures the multitude of considerations involved in dam decision making. Please take this opportunity to provide any questions, comments, or suggestions about the material on our pre-survey.

(29) Questions, comments, suggestions?

POST-SURVEY FOR STUDENT WORKSHOP

Thank you for agreeing to fill out this survey. The purpose of this survey is to collect individual participant preference information after the Dam Decision Support Workshop. Your answers will serve as useful reference in the assessment of the decision support tools used in the workshop. Your **feedback** will also help us to improve the models for decision support moving forward.

Email address:________________

First Name:__________________

Last Name:__________________

Section 1: Dam Decision Alternatives

(1) To what extent do you prefer the following decision alternatives? Please check one box for every row.

	Strongly DO NOT prefer	DO NOT prefer	Neutral	Prefer	Strongly prefer
Removal of a **non-powered** dam.					
Removal of a **powered** dam.					
Repair or maintenance to a **non-powered** dam					
Repair or maintenance to a **powered** dam.					
Fish passage improvements at a **powered** dam.					
Fish passage improvements at a **non-powered** dam.					
Turbine or other electromechanical equipment improvements at an existing **powered** dam.					
Turbine installation (power capacity expansion) at an existing **non-powered** dam.					
Turbine installation (power capacity expansion) *and* fish passage improvements at an existing **powered** dam.					
Turbine installation (power capacity expansion) *and* fish passage improvements at an existing **non-powered** dam.					

Section 2: Issues Related to Dams

(2) Please rate how important you consider each of the following issues related to **dams**. Please check one box for every row.

	Not Important	Somewhat Unimportant	Neither important nor unimportant	Somewhat Important	Extremely Important
Indigenous cultural heritage					
Industrial historical value					
Aesthetics					
Town/City Identity					
Fish survival					
Ecosystem Health					

	Not Important	Somewhat Unimportant	Neither important nor unimportant	Somewhat Important	Extremely Important
Water quality					
Reservoir storage					
Breach hazard potential					
Invasive species					
Number of properties impacted					
Recreation opportunities					
Employment					
Annual electricity generation					
Flood control					
Changes in natural flows					
Changes in sediment transport					
Changes in reservoir water levels					
River or stream access					
Annuitized project costs					
Economic development					
Endangered species					
Climate change					
Changes in land use					
Annual CO_2 emissions avoided					
Erosion					

(3) In the workshop, you had an opportunity to consider single dams as a part of a coordinated multi-dam decision. Do you prefer decision making involving single dams or multiple dams? Check one.

____Single dams
____Multiple dams

(4) Please explain your response from question (3). Why do you prefer this type of decision making?

Section 3: Workshop Evaluation

(5) How much did you LIKE or DISLIKE the workshop activity? Check one for every row.

	Does not apply	Disliked a lot	Somewhat disliked	Neither liked nor disliked	Somewhat liked	Liked a lot
Overall experience						
Group negotiation activity						
Overall workshop facilitation style						
Instruction on how to complete activities						
Bar graphs that resulted from the Dam Decision Support Tool						
Comparing your individual results from the Dam Decision Support Tool						
Multi-dam scenario maps						
Rose plots						
Dam Factsheets						
How the results were presented						
Powerpoint presentation (in the beginning)						
Dam Decision Support Tool						
Discussion/debrief						

(6) How much did you **learn** from the workshop activity? Check one box for every row.

	Does not apply	Did not learn anything	Learned something	Learned a lot
Overall experience				
Group negotiation activity				

	Does not apply	Did not learn anything	Learned something	Learned a lot
Overall workshop facilitation style				
Instruction on how to complete activities				
Bar graphs that resulted from the Dam Decision Support Tool				
Comparing your individual results from the Dam Decision Support Tool				
Multi-dam scenario maps				
Rose plots				
Dam Factsheets				
How the results were presented				
Powerpoint presentation (in the beginning)				
Dam Decision Support Tool				
Discussion/debrief				

(7) Evaluation of this workshop by participants is critical to the development of useful decision tools. Please rate the following aspects of the workshop. (Check one for every row). NOTE: for this question, “the model” refers to the Dam Decision Support Tool AND the Multi-Objective Genetic Algorithm (MOGA) unless otherwise specified.

	Strongly DISAGREE	DISAGREE	Neither agree nor disagree	AGREE	Strongly AGREE
Decision CRITERIA were distinct, independent, relevant and meaningful to me.					
Decision ALTERNATIVES were distinct, independent, relevant and meaningful to me.					

	Strongly DISAGREE	DISAGREE	Neither agree nor disagree	AGREE	Strongly AGREE
The decision problem analysis was intuitive; the breakdown of the problem into decision criteria and decision alternatives was an appropriate choice for the model.					
The model was robust.					
The group negotiation process did not appear vulnerable to manipulation by strategic participation or voting.					
The model was practical and well-suited to the specific application.					
The model appears to have been developed based on stakeholder input.					
The model is user-friendly.					
The group negotiation process was well-suited to the specific application and simulated a real decision-making process.					
Appropriate units or relative quantities were considered and used explicitly when asking about my preferences.					
The process facilitated consensus-building and outlined structured standards for conflict resolution.					
The model addressed fairness explicitly both qualitatively and quantitatively.					
The group negotiation process gave equal access, equal standing, and balanced influence to all participants.					
I actively participated in model construction and the resulting model addressed my key management needs.					
The group negotiation process provided opportunities for me to ask clarifying questions, actively incorporated my input/feedback, and inspired my trust.					

	Strongly DISAGREE	DISAGREE	Neither agree nor disagree	AGREE	Strongly AGREE
The process laid the groundwork for trust-building among myself and other participants through facilitated conversation.					
The outcome was realistic, useful, and it could be made actionable.					
Equity was explicitly considered in the decision process. The outcome was equitable for all participants.					
Researcher objectives and instructions were clearly stated and transparent to me throughout the decision-making process.					
The outcome was environmentally sustainable; or, environmental sustainability was addressed.					
The outcome was socially sustainable; or, social sustainability is addressed.					
The outcome was economically sustainable; or, economic sustainability was addressed.					
The outcome was technically sustainable; or, technical sustainability was addressed.					
The process encouraged my individual learning, and provided materials to facilitate my learning beyond the workshop.					
The process encouraged group learning, or learning from one another, including new, shared understanding leading to action beyond the workshop.					
The workshop facilitated trust-building.					
The model and group negotiation process were transparent.					
The guidance/facilitation was adapted to the needs of the participants.					
The model was accessible; it made sense.					
The process was accessible; it made sense.					

	Strongly DISAGREE	DISAGREE	Neither agree nor disagree	AGREE	Strongly AGREE
The workshop enhanced my own capacity for decision making.					
I would use a similar process in my own decision making.					

(8) When using the Dam Decision Support Tool, did you prefer working
____Individually
____ In a group
____ I liked both
____ I did not like either

(9) Please explain your response to question (8). Why do you prefer the choice you selected, specifically?

(10) What additional information would you like to see in the Dam Factsheets, if any?

(11) If you responded to question 10, how would this additional information improve your ability to make a dam decision?

(12) Please discuss anything in particular you learned from the workshop or anything you found interesting.

(13) Please discuss any particular challenges or difficulties you encountered in the workshop.

(14) Please discuss any suggestions for improvement you have for future workshops like this.

Thank you for your responses!

Thank you for filling out the post-survey. Your responses will help us to create a Dam Toolbox that better captures the multitude of considerations involved in dam decision making. Please take this opportunity to provide any questions, comments, or suggestions about the workshop experience or materials.

(15) Questions, comments, suggestions?

4. Study 3 Pre-/Post-Survey

PRE-SURVEY FOR DAM DECISION SUPPORT WORKSHOP

You have been asked to participate in a research project described below. You must be at least 18 years old to participate in this research project.

Description of the project: This study examines decision making preferences and processes about dams. We hope to learn about preferences for ecosystem services from dams, common arguments for and against dams, and how collaborative decision processes impact decisions about dam removal, rehabilitation, and upgrading.

What will be done: You have been invited to participate in a pre-/post-survey. The purpose of this survey is to collect individual participant preference information prior to a Dam Decision Support Workshop. Your answers will help inform the assessment of the decision support tools designed for participatory use in the workshop. The pre-survey is expected to take 1 hour.

Risks or discomfort: It is unlikely that you will incur any risks or will experience any discomfort as a result of participating in this study.

Benefits of this study: Although there may be no direct benefit to you from participation in this study, the researchers may learn more about how people use science to make decisions about dams and about how collaboration impacts decision making, resulting in better decision making about dams.

Confidentiality: Your part in this study is confidential. None of the information will identify you by name.

Decision to quit at any time: The decision to take part in this survey is up to you. You do not have to participate. If you decide to take part in the survey, you may quit at any time. Whatever you decide will in no way penalize you. If you wish to quit, simply close out of the web page. If you choose to take part in the survey, you may edit your responses after you submit.

You have read this information. Your response to this survey means that you understand the information and you agree to participate in this study. If you run out of time or wish to edit your responses later, simply skip head and submit the survey and use your invitation link to access again. We recommend that participants select "send me a copy of my responses" upon exiting.

Section 1: Participant Information

a. Email Address
b. First Name
c. Last Name

Section 2: Dams and Rivers

(1) In your opinion, what is the SINGLE most important aspect of a dam and its reservoir? List only one.
(2) In your opinion, what is the SINGLE most important aspect of a free-flowing river? List only one.
(3) What are the THREE most common arguments you encounter to keep a dam? List three.
(4) What are the THREE most common arguments you encounter to remove a dam? List three.
(5) Do you prefer decision making involving single dams or multiple dams? Check one

a. Single dams
b. Multiple dams
c. Other (write-in)

(6) Please explain your response to question (5). Why do you prefer this type of decision making?

Section 3: Issues and Alternatives Related to Dams

IMPORTANT: In the previous questions, we asked you to answer based on your opinion and personal/professional thoughts. At the upcoming workshop, you have been invited to represent a specific entity (e.g., company, organization, agency, group of people, etc) in a negotiation process that will attempt to simulate some aspects of real dam decision-making processes where different entities come together with different missions/agendas. For Questions 7-8, please answer with that official entity representative "hat" on as best you can. If the entity has a specific mission, use that to guide you. As a reminder, your answers are confidential, and the entity you are representing will not see these answers, so do not worry about getting it exactly right. Just please try your best to represent your company/organization/agency/group/etc.

(7) To what extent does the entity you are representing in the workshop prefer the following decision alternatives? (Check one for every row)

	Strongly do not prefer	Do not prefer	Neutral	Prefer	Strongly prefer
Removal of a dam					
Repair or maintenance to a dam					
Fish passage improvements at a dam					
Turbine or other electromechanical equipment improvements at a dam					
Turbine or other electromechanical equipment improvements *and* fish passage improvements at a dam					

(6) How important does the entity consider each of the following issues related to dams? (Check one for every row)

	Not at all Important	Unimportant	Neither important nor unimportant	Important	Extremely Important
Sea-run fish habitat area					
River recreation area					
Reservoir storage					

Annuitized project cost (e.g. cost of fish passage improvements, dam removal, turbine installation spread out over time)					
Number of properties impacted					
Breach damage potential					
Annual electricity generation					
Annual carbon dioxide (CO2) emissions reduction					
Indigenous cultural traditions and lifeways					
Community identity					
Industrial historical importance					
Aesthetic value					
Public health					
Socio-environmental justice					

(7) Are there any issues we missed? If so, please list them here.

Section 4: Penobscot River Dams*

In the next sections, you will be asked to consider several dam projects coming up for Federal Energy Regulatory Commission (FERC) relicensing in the Penobscot River Watershed: Medway Dam, Ripogenus Dam, West Enfield Dam, and the Penobscot Mills Project (also referred to as Great Northern Paper Mill and including 5 dams: Millinocket/Quakish, East Millinocket, North Twin, Dolby, and Millinocket Lake). During any relicensing process, the hydropower operation license application is opened to public comment, water quality certifications are issued, and federal and state agencies submit formal opinions about the operation of the dam.

For each of the questions here, you will rate a series of decision criteria (i.e., attributes or issues related to dams) for a specific dam. You will be asked about possible options for the dam, based on your prior knowledge of the dam site. PLEASE USE YOUR PERSONAL AND/OR PROFESSIONAL EXPERIENCE TO HELP YOU ANSWER THESE QUESTIONS - you are not representing your entity in the same way you were in questions 7-8. Draw on ANY personal and/or professional experience you have to answer these questions.

It is important to consider each decision criterion in the context of the specific dam because participants' anonymous, aggregated responses to these questions will be used as data in the October 3rd workshop. The questions may appear repetitive, but where possible, they must be evaluated for each decision alternative at each dam. Please consider carefully.

If you do not feel you have enough knowledge of the dam site to answer a question or section, you may select "I don't know" for specific questions, or skip questions/sections as needed. Reminder: you may also skip forward to the end, submit, and come back later to edit your responses if you run out of time to finish.

**NOTE TO THE READER: Section 6 is representative of the set of questions that the participants will encounter in sections 7 – 13, for each of the other 7 dams identified in section 5 (West Enfield, Ripogenus, Millinocket/Quakish, East Millinocket, Dolby, North Twin, and Millinocket Lake). Participants may skip answering about dams with which they are not familiar.*

In each of these dam sections, participants are asked about six decision criteria: aesthetics, community identity, indigenous cultural traditions and lifeways, industrial historical importance, public health, and socio-environmental justice. Participants are asked to consider the same set of 5 decision alternatives (Remove Dam, Improve Fish Passage, Improve Hydropower Generation, Improve BOTH Fish AND Hydro, and Keep and Maintain) for each decision criterion.

Section 5: MEDWAY DAM

Each of the hypothetical decision alternatives (e.g. remove dam, improve fish passage, improve hydropower generation, etc.) listed below is specific to the Medway Dam. You may want to reference the Medway Dam Factsheet, Decision Matrix, and Decision Alternative Descriptions at this time.

If you do not feel you have enough knowledge of Medway Dam to answer these questions, please select "Skip this section" here (so we know why you did not answer these questions), scroll to the bottom of the page, and click Next to proceed to the next section.

- o Skip this section
- o I will answer this section

Decision Criterion 1: Aesthetics

A rating to convey the importance of improving or preserving aesthetics (e.g., appearance, scenic value, smell, sound) at the dam site.

(9) Consider each option (e.g., remove dam, improve hydropower generation) one at a time. How would you rate the state of AESTHETICS at the MEDWAY DAM site if an option happened? For example, if you think the aesthetics of the existing dam are good, you would select a high rating (4 -5) for “keep and maintain dam”. If you think the aesthetics would be greatly improved by removing the dam, you would select a high rating for “remove dam”.

Medway Dam **FERC No. P-2666** **License exp: 2029**	1= Poor	2	3	4	5 = Excellent	I don’t know
Remove Dam						
Improve Fish Passage						
Improve Hydropower Generation						
Improve Hydropower Generation and Fish Passage						
Keep and Maintain Dam						

Decision Criterion 2: Community Identity

A rating to convey the importance of the dam for preserving the existing community identity for residents living along or on islands within the river.

(10) Consider each option (e.g., remove dam, improve hydropower generation) one at a time. How would you rate COMMUNITY IDENTITY at the MEDWAY DAM site if an option happened? For example, if you think community identity is currently strongly linked to the existing dam, you would select a high rating (4 – 5) for "keep and maintain dam." If you think a free-flowing river at that site would contribute to a strong sense of community identity, you would select a high rating for "remove dam".

Medway Dam **FERC No. P-2666** **License exp: 2029**	1= Poor	2	3	4	5 = Excellent	I don't know
Remove Dam						
Improve Fish Passage						
Improve Hydropower Generation						
Improve Hydropower Generation and Fish Passage						
Keep and Maintain Dam						

Decision Criterion 3: Indigenous Cultural Traditions and Lifeways

A rating to convey the importance of the dam for preserving/restoring the traditions and lifeways of indigenous people whose culture is deeply entwined with the river they have used for millennia.

(11) Consider each option (e.g., remove dam, improve hydropower generation) one at a time. How would you rate strengthening the practice of INDIGENOUS CULTURAL TRADITIONS AND LIFEWAYS at the MEDWAY DAM site if the option happened? For example, if you think the practice of indigenous cultural traditions and lifeways are currently strongly supported by the existing dam, you would select a high rating (4 – 5) for "keep and maintain dam". If you think a free-flowing river at that site would strengthen the practice of indigenous cultural traditions and lifeways, you would select a high rating for "remove dam".

Medway Dam **FERC No. P-2666** **License exp: 2029**	1= Poor	2	3	4	5 = Excellent	I don't know
Remove Dam						
Improve Fish Passage						

Improve Hydropower Generation						
Improve Hydropower Generation and Fish Passage						
Keep and Maintain Dam						

Decision Criterion 4: Industrial Historical Importance

A rating to convey the importance of the dam for preserving/restoring the industrial history at the site.

(12) Consider each option (e.g., remove dam, improve hydropower generation) one at a time. How would you rate INDUSTRIAL HISTORICAL IMPORTANCE at the MEDWAY DAM site if the option happened? For example, if you think the existing dam holds a lot of industrial historical importance, you would select a high rating (4 -5) for "keep and maintain dam". If you think a free-flowing river at that site would hold a lot of industrial historical importance, you would select a high rating for "remove dam".

Medway Dam **FERC No. P-2666** **License exp: 2029**	1= Poor	2	3	4	5 = Excellent	I don't know
Remove Dam						
Improve Fish Passage						
Improve Hydropower Generation						
Improve Hydropower Generation and Fish Passage						
Keep and Maintain Dam						

Decision Criterion 5: Public Health

A rating to convey the importance of public health, which is connected to air, water, and land pollution.

(13) Consider each option (e.g., remove dam, improve hydropower generation) one at a time. How would you rate PUBLIC HEALTH at the MEDWAY DAM site if the option happened? For example, if you think the existing dam contributes positively to good public health, you would select a high rating (4 – 5) for "keep and maintain dam". If you think a free-flowing river at that site would contribute a lot to good public health, you would select a high rating for "remove dam".

Medway Dam **FERC No. P-2666**	1= Poor	2	3	4	5 = Excellent	I don't know

License exp: 2029						
Remove Dam						
Improve Fish Passage						
Improve Hydropower Generation						
Improve Hydropower Generation and Fish Passage						
Keep and Maintain Dam						

Decision Criterion 6: Socio-Environmental Justice

A rating to convey the importance of socio-environmental justice issues (e.g., negative environmental effects that target disadvantaged groups - people of lower socio-economic status or with less political or economic power).

(14) Consider each option (e.g., remove dam, improve hydropower generation) one at a time. How would you rate the preservation or improvement of SOCIO-ENVIRONMENTAL JUSTICE at the MEDWAY DAM site if the option happened? For example, if you think the existing dam preserves socio-environmental justice (e.g., it does NOT harm people from disadvantaged groups), you would select a high rating (4 – 5) for "keep and maintain dam". If you think a free-flowing river at that site would improve socio-environmental justice (e.g., the dam DOES harm disadvantaged groups, and their situation would be improved if the dam was removed), you would select a high rating for "remove dam".

Medway Dam **FERC No. P-2666** **License exp: 2029**	1= Poor	2	3	4	5 = Excellent	I don't know
Remove Dam						
Improve Fish Passage						
Improve Hydropower Generation						
Improve Hydropower Generation and Fish Passage						
Keep and Maintain Dam						

Section 6-12: *Repeat of section 6 for each of the following dams: West Enfield, Ripogenus, East Millinocket, Millinocket/Quakish, Dolby, North Twin, and Millinocket Lake.*

Section 13: Demographics

This final section of the survey includes a standard set of demographic questions to help us analyze survey responses. All data will be kept confidential. You may skip any question.

(57) How many years have you been working with rivers/dams?

a. Under 1 year

b. 1-2 years

c. 3-5 years

d. 6-10 years

e. 11-15 years

f. 16-20 years

g. More than 20 years

(58) How old are you?

a. Under 20 years

b. 21-25 years

c. 26-30 years

d. 31-35 years

e. 36-40 years

f. 41-45 years

g. 46-50 years

h. 51-55 years

i. 56-60 years

j. 61-65 years

k. 66-70 years

l. Over 70 years

(59) What is your gender

a. Female

b. Male

c. Non-conforming/non-binary/third gender

d. Prefer not to say

e. Other (fill in the blank)

(60) What is the highest level of education you have completed? (select one)

a. Some high school

b. High school graduate or GED

c. Some college or Associate's degree

d. College graduate (Bachelor's degree or equivalent)

e. Postgraduate (Master's, Doctorate, Law, or other degree)

(61) Which of the following represents your current employment status? (Select all that apply)

a. Student

b. Employed full-time

c. Employed part-time

d. Flexible employment/contract employment

e. Homemaker

f. Unemployed

g. Retired (not working)

h. Other (fill in the blank)

Section 14: Thank you for your responses!

Thank you for filling out the pre-survey. Your responses will help us to create a workshop experience that better captures the multitude of considerations involved in dam decision making. Please take this opportunity to provide any questions, comments, or suggestions about the material on our pre-survey.

If you wish to edit your responses later, simply use your invitation link to access again. We recommend that participants select "send me a copy of my responses" upon exiting the survey so that you can review and decide whether to edit at a later time.

(62) Questions, comments, suggestions?

POST-SURVEY FOR DAM DECISION SUPPORT WORKSHOP

Thank you for agreeing to fill out this survey.

What will be done: You have been invited to participate in a post-survey, expected to take 20 - 30 minutes. The purpose of this survey is to collect individual participant preference information after a Dam Decision Support Workshop. Your answers will serve as a helpful reference in the assessment of the decision support models used in the workshop. Your feedback will also help us to improve the models for decision support moving forward.

Risks or discomfort: It is unlikely that you will incur any risks or will experience any discomfort as a result of participating in this study.

Benefits of this study: Although there may be no direct benefit to you from participation in this study, the researchers may learn more about how people use science to make decisions about dams and about how collaboration impacts decision making, resulting in better decision making about dams.

Confidentiality: Your part in this study is confidential. None of the information will identify you by name.

Decision to quit at any time: The decision to take part in this survey is up to you. You do not have to participate. If you decide to take part in the survey, you may quit at any time. Whatever you decide will in no way penalize you. If you wish to quit, simply close out of the web page. If you choose to take part in the survey, you may edit your responses after you submit.

You have read this information. Your response to this survey means that you understand the information and you agree to participate in this study. If you run out of time or wish to edit your responses later, simply skip head and submit the survey and use your invitation link to access again. We recommend that participants select "send me a copy of my responses" upon exiting.

Section 1: Participant Info

a. Email Address
b. First Name
c. Last Name

Section 2: Issues and Alternatives Related to Dams

IMPORTANT: At the workshop, you represented a specific entity (e.g., company, organization, agency, group of people, etc) in a negotiation process that attempted to simulate some aspects of real dam decision-making processes where different entities come together with different missions/agendas. For Questions 1-2 ONLY, please answer with that official entity representative "hat" on as best you can. If the entity has a specific mission, use that to guide you. As a reminder, your answers are confidential, and the entity you are representing will not see these answers, so do not worry about getting it exactly right. Just please try your best to represent your company/organization/agency/group/etc.

(1) To what extent does the entity you represent prefer the following decision alternatives? (Check one for every row)

	Strongly do not prefer	Do not prefer	Neutral	Prefer	Strongly prefer
Removal of a dam					
Repair or maintenance to a dam					
Fish passage improvements at a dam					
Turbine or other electromechanical equipment improvements at a dam					
Turbine or other electromechanical equipment improvements *and* fish passage improvements at a dam					

Section 3: Issues Related to Dams

(2) How important does the entity consider each of the following issues related to dams? (Check one for every row)

	Not at all Important	Unimportant	Neither important nor unimportant	Important	Extremely Important
Sea-run fish habitat area					
River recreation area					
Reservoir storage					
Annuitized project cost (e.g. cost of fish passage improvements, dam removal, turbine installation over time)					
Number of properties impacted					
Breach damage potential					
Annual electricity generation					
Annual carbon dioxide (CO_2) emissions reduction					
Indigenous cultural traditions and lifeways					
Community identity					
Industrial historical importance					
Aesthetic value					
Public health					
Socio-environmental justice					

(3) In the workshop, you had an opportunity to consider single dams as a part of a coordinated multi-dam decision. Do you prefer decision making involving single dams or multiple dams? Check one

d. Single dams
e. Multiple dams
f. Other (write-in)

(4) Please explain your response to question (3). Why do you prefer this type of decision making?

Section 4: Workshop Evaluation

(5) How much did you LIKE or DISLIKE the workshop activity/material? (Check one for every row)

	Does not apply	Disliked a lot	Somewhat disliked	Neither liked nor disliked	Somewhat liked	Liked a lot

Overall experience						
Overall workshop facilitation style						
Powerpoint presentation						
Instruction on how to complete activities						
Dam Factsheets						
Decision Matrices						
Posters hanging up around the room						
Dam Decision Support Tool						
Individual preference elicitation activity (i.e., working with the tool on your own)						
Group negotiation activity						
Bar graphs that resulted from the Dam Decision Support Tool						
Multi-dam map recommendation that resulted from the Dam Decision Support Tool						
Comparing your individual results from the Dam Decision Support Tool with the group's						
How the results were presented/interpreted						
Discussion/debrief						

(6) How much did you LEARN from the workshop activity/material? (Check one for every row)

	Does not apply	Did not learn anything	Learned something	Learned a lot
Overall experience				
Overall workshop facilitation style				

Powerpoint presentation (in the beginning)				
Instruction on how to complete activities				
Dam Factsheets				
Decision Matrices				
Posters hanging up around the room				
Dam Decision Support Tool				
Individual preference elicitation activity (i.e., working with the tool on your own)				
Group negotiation activity				
Bar graphs that resulted from the Dam Decision Support Tool				
Multi-dam map recommendation that resulted from the Dam Decision Support Tool				
Comparing your individual results from the Dam Decision Support Tool with the group's				
How the results were presented/interpreted				
Discussion/debrief				

(7) Evaluation of this workshop by participants is critical to the development of useful decision tools. Please rate the following aspects of the workshop (check one for every row). NOTE: for this question, "the model" refers to the Dam Decision Support Tool; the "workshop outcome" refers to the outcome of the group negotiation process.

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
The user interface of the model is intuitive, comfortable, and straightforward.					
It was clear in the model how user preferences were combined with underlying data and calculations to result in the outcome.					
The decision problem was clearly bounded and defined at the outset of the workshop					

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
I gained new knowledge in the workshop that I didn't have before					
Participating in the workshop shifted my goals and/or values.					
The materials provided to me will help facilitate my learning beyond the workshop.					
I can easily see how the model presented in the workshop could be used in real-world applications.					
The model appears to have been developed based on stakeholder input.					
The group negotiation process was straightforward and clearly and appropriately structured.					
The goals and objectives of the workshop were met.					
The group negotiation process is well-suited to real-world application					
The group negotiation process simulates real decision making processes and is adaptable.					
The set of decision criteria included in the model represents the full set of priority issues surrounding the decision to be made.					
The decision criteria were accurate.					
The decision criteria were both relevant and meaningful to me.					
The decision alternatives were representative of the real decision landscape; they were relevant and meaningful to me.					
Goals and objectives were clearly stated, easy to understand, and transparent throughout the workshop.					
The mix of people at the workshop represented the appropriate level of diversity of perspectives and was balanced across top-priority issues.					
I am committed to implementing the outcome.					
Other participants demonstrated commitment to implementing the outcome.					
The outcome was realistic, useful, and it could be made actionable.					

	Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
Equity was explicitly considered in the group negotiation process.					
The outcome was equitable for all participants.					
All participants had an equal voice in the group negotiation process.					
The financial benefits of the decision outweigh the costs.					
The workshop outcome would likely improve environmental sustainability.					
The workshop outcome would likely improve social sustainability.					
The workshop outcome is physically (technologically) possible.					
The workshop outcome is possible within regulatory constraints.					
The model was accurate; it made sense.					
I actively participated in model construction and my feedback was incorporated into model development and refinement at multiple stages.					
I felt like I could express myself with ease throughout the workshop.					
Other participants in the workshop showed respect for my ideas and contributions					
I plan to continue working with other people from the workshop toward future actions that build off of the outcome reached in the workshop.					

(8) Please explain any of your answers above (Q7) that require further clarification.

(9) When using the Dam Decision Support Tool, did you prefer working individually, or in a group?

a. Individually
b. In a group
c. I liked them both
d. I did not like either

(10) Please explain your response above. Why do you prefer the selected choice, specifically?

(11) What additional information would you like to see in the Dam Factsheets, if any?

(12) If you responded to question 10, how would this additional information improve your ability to make a decision about a dam?

(13) Please discuss anything in particular you learned from the workshop or anything you found interesting.

(14) Please discuss any particular challenges or difficulties you encountered in the workshop.

(15) Please discuss any suggestions for improvements to future workshops like this.

Section 5: Thank you for your responses!

Thank you for filling out the post-survey. Your responses will help us to create a Dam Toolbox that better captures the multitude of considerations involved in dam decision making. Please take this opportunity to provide any questions, comments, or suggestions about the workshop experience or materials.
If you wish to edit your responses later, simply use your invitation link to access again. We recommend that participants select "send me a copy of my responses" upon exiting the survey so that you can review and decide whether to edit at a later time.

(16) Questions, comments, suggestions?

APPENDIX M: MCDA OUTCOMES

Studies 2 and 3 had similar ranked MCDA outcomes (Figure M1) but were somewhat differently in terms of the driving decision criteria (Figure M2). For instance, dam removal was a top-ranked decision alternative at Medway Dam, based on average individual participant preference values in each study, but sea-run fish habitat area seems to have been more of a factor in Study 3 than in Study 2, while annuitized project costs and annual electricity generation seems to have played a more important role in MCDA rankings in Study 2 than in Study 3.

Figure M1. Final MCDA Score comparison for three dams.

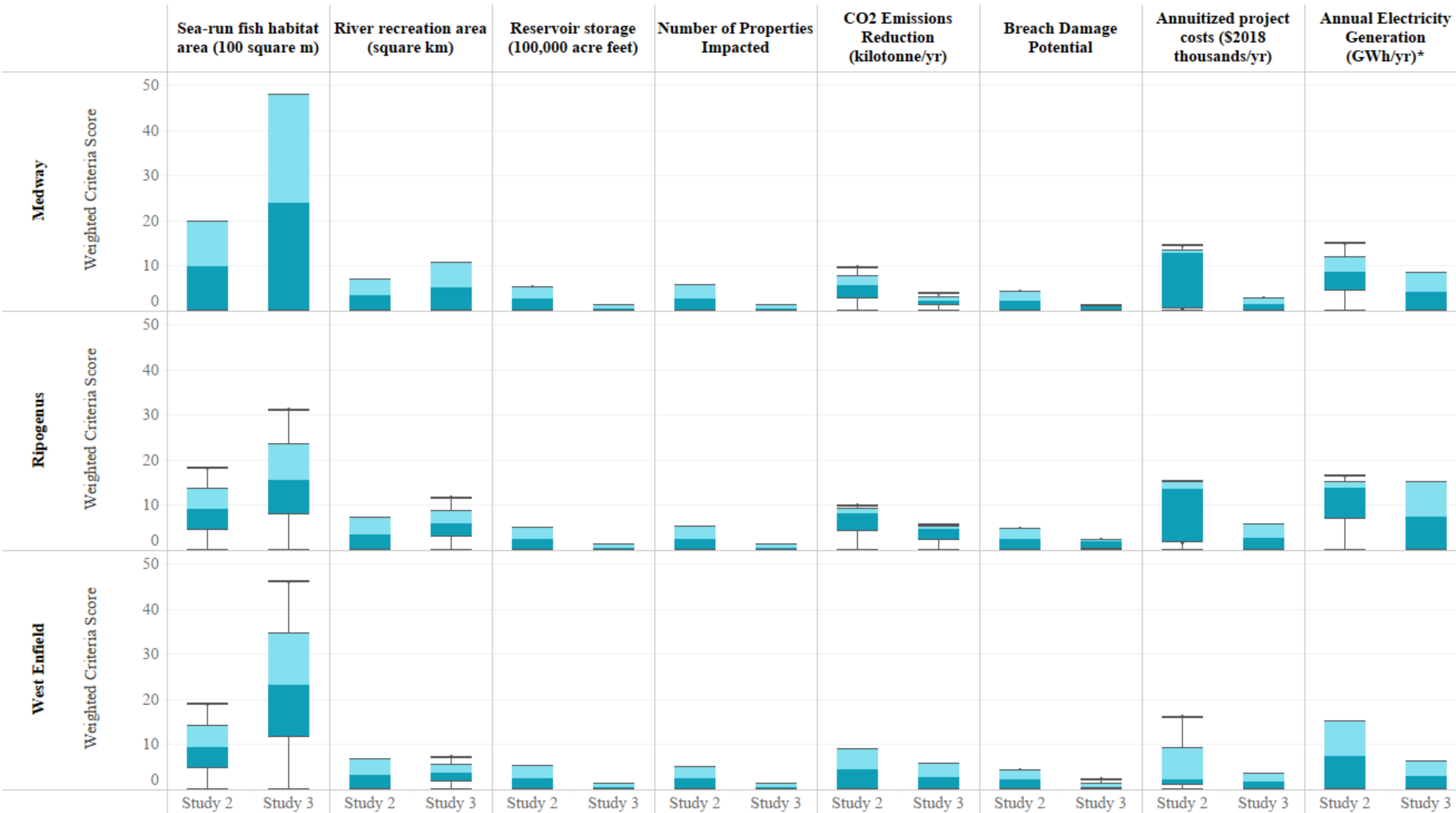


Figure M2. Criteria score comparison across three dams.

APPENDIX N: POSTERS FOR STUDY 3 (OCTOBER 2019 WORKSHOP 3 WITH STAKEHOLDERS)

Poster images below give a glimpse into what stakeholder participants saw hanging around the room during the third and final workshop in October 2019. We developed posters to supplement the Dam Factsheets and Data Tables with site-specific information, as well as provide additional detail about the decision criteria and alternatives. We also included an MCDA poster to elaborate on the WS model mechanics. Finally, we printed a large color image of the Penobscot Watershed map that we showed participants in study 2 – 3 to give them a reference for understanding the multi-dam result. While we did point to posters in instruction about the decision scenario and later on in discussion, posters were mostly intended for participants to browse during coffee breaks, lunch, or at the beginning of the day during set up.

5 Decision Alternatives

KEEP & MAINTAIN

"Do-nothing" or "business-as-usual"

- Lowest-cost option in near-term; costs borne by owner
- May appeal to parties interested in preserving the area's industrial history, community identity, aesthetic value of impoundment
- No change to reservoir storage volume, river recreation area, annual electricity generation, or number of properties abutting the reservoir
- Impoundment will continue to present a barrier to sea-run fish species, thereby negatively impacting their survival
- Only bare minimum updates for safety

IMPROVE FISH PASSAGE

Install some type of fish passage structure

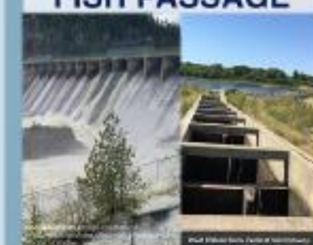
- May be required by law depending on the species migrating in the waterway
- May increase survival for one or more sea-run fish species
- May improve angling in river
- May provide learning opportunities for citizens and students
- Costs are typically high and borne by owner with potential help from agencies

IMPROVE HYDROPOWER

Increase hydropower generation capacity

- May reduce greenhouse gas emissions that contribute to climate change
- Costs are high and borne by owner but may be recouped through market returns over the project's lifetime
- May alter flows, confuse fish, catch fish in grates, or kill them
- Reservoir storage may change depending on operations

IMPROVE HYDROPOWER & FISH PASSAGE



Install some type of fish passage AND increase hydropower generation capacity

- May be required by law depending on the species migrating in the waterway
- May increase survival for one or more sea-run fish species
- May improve angling in river
- May provide learning opportunities for citizens and students
- May reduce greenhouse gas emissions that contribute to climate change
- Annual electricity generation will increase
- May alter flows, confuse fish, catch fish in grates, or kill them
- Costs are typically high and borne by owner
- Revenue may help recoup costs over the project's lifetime

REMOVE DAM

Dam is removed completely, allowing river to flow freely

- Creates greater connectivity for fish passage and river recreation, bolstering sea-run fish populations, and improving benthic (riverbed) aquatic communities
- May improve local water quality, regulate water temperature, and provide additional tourism/fishing opportunities
- Will likely return river to "natural" flows
- May create temporary mud flats and/or release toxic or harmful impounded sediments
- Eliminates lake-dwelling wildlife habitat & local flatwater recreation opportunities
- Reduces reservoir storage volume
- Eliminates hydropower generation
- Near-term costs are typically high, with no direct market returns, outside funding may exist

Prepared by Sharon Klein and Emma Fox (with help from Sam Roy, Tyler Quiring, Catherine Ashcraft) for a Future of Dams Multi-Criteria Decision Analysis Workshop, October 2019

14 Decision Criteria: NINE estimated for Decision Support Tool

Cost

Annuitized Capital + Annual Operation & Maintenance

Assumptions:
- 20-yr investment lifetime; 6.2% discount rate (2)
- All costs inflation-adjusted to \$2018 using (3)
- Capital cost for Keep/Maintain = 0; Remove Dam from (6); Improve Hydro from (4); Improve Fish Passage from Hall et al.'s (5) equation for Fish & Wildlife Mitigation Costs (p.14), not including Fish Passage Mitigation costs because although there are endangered Atlantic salmon in the Penobscot River, the dams in this set are not required to pass them
- O&M cost for Millinocket Lake (only non-powered dam in set) \$1,000/yr (7)

How we calculate it (1,2):

$$C_a = C_C\left(\frac{r(1+r)^t}{((1+r)^t-1)}\right) + C_{OM},\ where$$

$$C_{OM,C} = 0.025\ C_C;\ or\ C_{OM,NC} = 225417P^{0.547}$$

C_a = annuitized project cost (\$2018/yr)
C_C = capital cost of project (\$2018)
r = discount rate
t = investment lifetime
C_{OM} = operation & maintenance cost (\$2018/yr)
$C_{OM,C}$ = C_{OM} for decision alternatives that include capital cost
$C_{OM,NC}$ = C_{OM} for decision alternatives that do not include capital cost

Relevant Data Sources:

(1) W. Short, D.J. Packey, T. Holt. "A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies", National Renewable Energy Laboratory (NREL), NREL/TP-462-5173, 1995.

(2) P. W. O'Connor, S. T. DeNeale, D. R. Chalise, E. Centurion, and A. Maloof, "Hydropower Baseline Cost Modeling, Version 2," Oak Ridge National Laboratory (ORNL), ORNL/TM-2015/471, Sep. 2015.

(3) https://www.calculator.net/inflation-calculator.html

(4) Kleinschmidt Associates, "Maine Hydropower Study," 2015.

(5) D. Hall, R.T. Hunt, K.S. Reeves, G.R. Carroll, "Estimation of economic parameters of US hydropower resources," EERE Publication and Product Library, INEEL/EXT-03-00662, 2003.

(6) B. Blachly, E. Uchida, "Estimating the Marginal Cost of Dam Removal" (2017). Environmental and Natural Resource Economics Working Papers. Paper 2.

(7) Colorado Parks & Wildlife Dam Maintenance Fact Sheet, 2015, https://cpw.state.co.us/Documents/Commission/2015/May/ITEM17-ColoradoParksandWildlife-fact-sheet-final.pdf.

CO_2 Reduction

Avoided Life Cycle Greenhouse Gas Emissions

Assumptions:
- Point-source CO_2 emissions data by fuel type for power generators in Maine (10) for petroleum, municipal solid waste (MSW), and coal – no life cycle data available for petroleum; coal life cycle estimate was less than point-source report
- Biomass (other than MSW) and other renewables carbon neutral
- Life cycle CO_{2eq} emissions for natural gas (11) and hydropower – separated by diversion and reservoir; including methane releases from reservoirs (8)
- Annual electricity generation from hydropower from Electricity Generation decision criterion listed below

$$Em_a = E_H(Em_{ME} - Em_H),$$

$$where\ Em_{ME} = \sum_{f \in F} p_f Em_f$$

Em_a = annual greenhouse gas (GHG) emissions avoided (kilotonnes CO_{2eq}/yr)
E_H = annual electricity generation from hydropower (GWh/yr)
Em_{ME} = annual GHG emissions produced by Maine electricity generation mix (kilotonnes CO_{2eq}/GWh); partial life cycle
Em_H = annual life cycle GHG emissions produced by hydropower (kilotonnes CO_{2eq}/GWh) (8)
F = the set of fuels generating CO_2 emissions when burned in Maine electricity generation mix (petroleum, natural gas, coal, municipal solid waste)
p_f = percentage of Maine electricity generation mix fuel f comprises (9)
Em_f = annual GHG emissions produced by fuel f (kilotonnes CO_{2eq}/GWh)

Relevant Data Sources:

(8) C. Song, K. Gardner, S.J.W. Klein, S. Pereira Souza, & W. Mo, 2018, Cradle-to-grave greenhouse gas emissions from dams in the United States of America. *Renewable and Sustainable Energy Reviews*, vol. 90, pp. 945-956.
(9) U.S. Energy Information Administration (EIA), 2017, "EIA-923 Monthly Generation and Fuel Consumption Time Series File", EIA923_Schedules_2_3_4_5_M_12_2017_Final_Revision.xlsx, Page 1 Generation and Fuel Data, https://www.eia.gov/electricity/data/eia923/.
(10) U.S. EIA, "Electricity Emissions by Plant and Region: Emissions by plant for CO_2, SO_2, and NO_x, Final Annual Data for 2017", Nov. 2018, https://www.eia.gov/electricity/data/emissions/.
(11) S.J.W. Klein, S. Whalley, 2015, Comparing the sustainability of U.S. electricity options through multi-criteria decision analysis (MCDA), *Energy Policy, 79*, 127-149.

Electricity Generation

Annual gigawatt-hours

Assumptions:
- Keep & Maintain, Improve Fish: reported values for average annual electricity generation from FERC licenses
- Improve Hydro and Improve Hydro & Fish: equations presented below with data from Maine Hydropower Study and FERC licenses

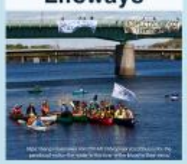
$$E_{Hn} = P \times h \times CF,\ where\ \ CF = \frac{E_H}{P \times h}$$

E_{Hn} = annual electricity generation from additional hydropower that could be installed at existing dam (GWh/yr)
P = additional rated hydropower capacity that could be installed at existing dam (GW) (4)
h = number of hours in a year
CF = annual capacity factor: percentage of time over the course of a year that a power generator meets its full rated capacity; calculated from power capacity and annual generation data found in FERC licenses

6 Social Criteria

Criteria identified as important by stakeholders in interview. Data values calculated as a weighted average from participant surveys response.

Indigenous Cultural Traditions & Lifeways



Preserving/ restoring culture & practices of indigenous people

Socio-Environmental Justice

Negative environmental effects targeting disadvantaged groups

Average of all Penobscot Nation survey responses

Public Health

Connected to air, water, land pollution

Industrial Historical Importance

Preserving/restoring the industrial history of the site

Aesthetic Value

Improving/preserving appearance, scenic value, smell, sound

Average of all survey responses

Community Identity

Preserving existing community identity for residents living along or on islands within the river

Average of all Penobscot Nation & municipal survey responses

Poster Prepared by Sharon Klein and Emma Fox for a Future of Dams Multi-Criteria Decision Analysis Workshop, October 2019

14 Decision Criteria: FIVE from Roy et al., 2018[1]

Sea-Run Fish Habitat Area

Atlantic salmon, Alewife, Blueback herring, American eel

Assumptions:
- 20% of available surface area exists along the river banks & is unsuitable for habitat due to river height fluctuations
- Alewife are the only species considered here that can spawn in lakes
- Calculating h_{ik} requires lake depth data to estimate the cumulative littoral zone available to alewife following our method to calculate reservoir storage volume.
- River and stream reaches that experience seasonal drying or that are located within tidal zones are excluded from analysis to reflect species' intolerance of these conditions for spawning and rearing

How we calculate it:

$$h_{ik} = \sum_{r \in g} [a_r t_{rk} v_{rk} \vartheta_{rk} \times 0.8]$$

h_{ik} = accessible functional habitat above dam i for species k (100s of m²)
r = an index for an unobstructed river reach above dam i
g = the set of river reaches immediately above dam i up to the next set of dams or river terminus
a_r = seasonal mean wetted area (m²) within reach r
t_{rk} = mean annual temperature quality factor in reach r for species k
v_{rk} = mean annual velocity quality factor in reach r for species k
ϑ_{rk} = a binary value identifying if the river reach r is accessible to species k

Relevant Data Sources:
(1) McKerrow, A. 2004. *Atlantic states marine fisheries commission.*
(2) Abbott, A. 2006. *Maine Atlantic salmon habitat atlas.*
(3) Houston, B., S. Lary, K. Chadbourne, and B. Charry. 2007. *Geographic distribution of diadromous fish in Maine.*
(4) Martin, E. H., and C. D. Apse. 2011. *Northeast aquatic connectivity: an assessment of dams on northeastern rivers.*
(5) Abbot, A. 2016. *Alewife ponds.*
(6) Olivero, A. P., and M. G. Anderson. 2008. *Northeast Aquatic Habitat Classification.* Boston, MA.
(7) USGS. 2017. *National Hydrography Dataset (NHD) plus, version 2.*
(8) Martin, E. H., and C. D. Apse. 2011. *Northeast aquatic connectivity: an assessment of dams on northeastern rivers.*
(9) Noonan, M. J., J. W. A. Grant, and C. D. Jackson. 2012. A quantitative assessment of fish passage efficiency. *Fish and Fisheries* 13(4):450–464.

River Recreation Area

Downstream Whitewater Recreation

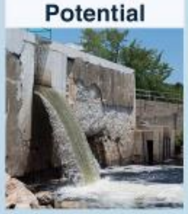
Assumptions:
- 20% of available surface area exists along the river banks where depth is too shallow for boating
- Limit river recreation season to when New England rivers are largely ice free (April to November); all reservoir dams only provide 20% of their storage capacity to recreational releases
- Use discharge thresholds of 300 & 2000 cfs, respectively, for canoe/kayak and whitewater rafts in New England, & combine recreational value of both

$$R_R = max\left[r\left(\sigma + \sum_{u \in n_{di}} \Upsilon_u\right)\right], \; where\; r = \sum_{r \in g} [a_r v_r d_r \times 0.8]$$

R_R = whitewater recreation, equal to the maximum connected river section between dams (km²)
r = functional river recreation area (m²)
σ = the mean fraction of time when recreational reaches above dam naturally meet minimum discharge requirements for boating
n_{di} = set of all dams upstream and including dam i, with index u for each dam
Υ_u = fractional capacity of upstream reservoir dams to provide recreational flows that increase the number of times when discharge requirements are met
g = the set of river reaches immediately above dam i up to the next set of dams or river terminus
a_r = surface area at reach r accessible to boat
v_r = velocity suitability factor for reach r

Relevant Data Sources:
(10) USGS (2016), NHDPlusV2. Available online: http://waterdata. usgs.gov/nwis/ (accessed on 1 August 2016)

Breach Damage Potential



0 = no/low
1 = medium
2 = high

Assumptions:
- State dam hazard level reported by *(11)*
- Indicates the potential for downstream property damage, injury, and death in the case of dam breach
- High hazard dams pose risk to life downstream if they fail or are inappropriately managed *(12)*
- Removal of medium to high hazard dams also removes the potential for loss of life due to mismanagement or dam breach

Relevant Data Sources:
(11) Maine office of GIS: impoundments and dams. Available Online: http://www.maine.gov/megis/catalog/ (accessed 1 September 2016)
(12) US Army Corps of Engineers (2014) *Safety of dams - Policy and procedures* doi:ER–1110–2–1156.

Reservoir Storage

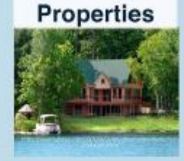
Cone Volume Method (13)

Relevant Sources:
(13) Hollister J, Milstead WB (2010) Using GIS to estimate lake volume from limited data. *Lake Reserv Manag* 26(3):194–199.

$$S = (V_t - V_b), \quad where\; V_t = \pi \sqrt{\frac{A}{\pi}\frac{d}{3}} \quad and\; V_b = \pi \frac{\sqrt{\frac{A}{\pi}}}{d} \frac{(d - d_{dam})^2}{3}$$

S = water storage capacity for a reservoir dam
V_t = reservoir volume (m³) from maximum depth to hydraulic height of dam (water height)
V_b = reservoir volume (m³) from maximum depth to base of dam
A = reservoir surface area (m²)
d = maximum depth of reservoir (m)
d_{dam} = hydraulic height of dam (m); *if data unavailable, then total height from base to top of dam is used*

Number of Properties



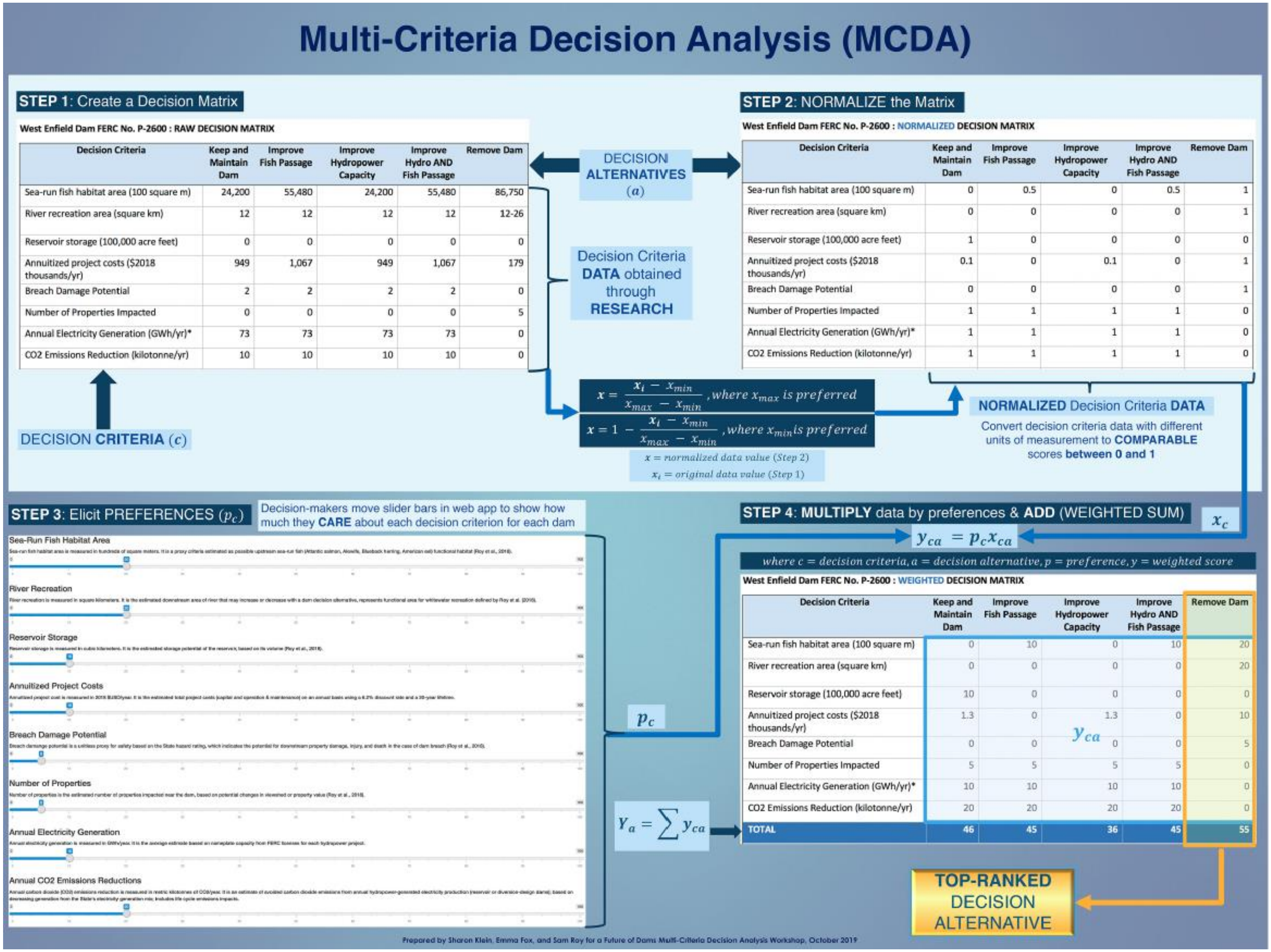
Limited to Properties Within 200 meters of the Dam and/or Reservoir

Assumptions:
- Properties that could potentially experience a significant change in viewshed, shoreline conditions, property value, or community identity by dam removal
- Not an indicator of quantity of property value change; influence of dam removals on property values is not clear (59, 60)

Address Location from:
(14) Maine Emergency Services Communication Bureau: Augusta, ME, USA. Available online: http://www.maine.gov/megis/catalog/ (accessed on 1 September 2016).

[1]All calculations, information, and data sources on this poster were adapted from: Roy, S., Uchida, E., De Sousa, S., Blachy, B., Fox, E., Gardner, K., Klein, S.J.W., Zydlewski, J., 2018, Damming decisions: A multi-scale approach to balance trade-offs among dam infrastructure, river restoration, and cost. *Proceedings of the National Academy of Sciences*, vol. 115, no.47, pp. 12069-12074, www.pnas.org/cgi/doi/10.1073/pnas.1807437115.

Poster Prepared by Sharon Klein, Emma Fox, and Sam Roy, for a Future of Dams Multi-Criteria Decision Analysis Workshop, October 2019



West Enfield Dam FERC No. P-2600 : RAW DECISION MATRIX

Decision Criteria	Keep and Maintain Dam	Improve Fish Passage	Improve Hydropower Capacity	Improve Hydro AND Fish Passage	Remove Dam
Sea-run fish habitat area (100 square m)	24,200	55,480	24,200	55,480	86,750
River recreation area (square km)	12	12	12	12	12-26
Reservoir storage (100,000 acre feet)	0	0	0	0	0
Annuitized project costs ($2018 thousands/yr)	949	1,067	949	1,067	179
Breach Damage Potential	2	2	2	2	0
Number of Properties Impacted	0	0	0	0	5
Annual Electricity Generation (GWh/yr)*	73	73	73	73	0
CO2 Emissions Reduction (kilotonne/yr)	10	10	10	10	0

West Enfield Dam FERC No. P-2600 : NORMALIZED DECISION MATRIX

Decision Criteria	Keep and Maintain Dam	Improve Fish Passage	Improve Hydropower Capacity	Improve Hydro AND Fish Passage	Remove Dam
Sea-run fish habitat area (100 square m)	0	0.5	0	0.5	1
River recreation area (square km)	0	0	0	0	1
Reservoir storage (100,000 acre feet)	1	0	0	0	0
Annuitized project costs ($2018 thousands/yr)	0.1	0	0.1	0	1
Breach Damage Potential	0	0	0	0	1
Number of Properties Impacted	1	1	1	1	0
Annual Electricity Generation (GWh/yr)*	1	1	1	1	0
CO2 Emissions Reduction (kilotonne/yr)	1	1	1	1	0

West Enfield Dam FERC No. P-2600 : WEIGHTED DECISION MATRIX

Decision Criteria	Keep and Maintain Dam	Improve Fish Passage	Improve Hydropower Capacity	Improve Hydro AND Fish Passage	Remove Dam
Sea-run fish habitat area (100 square m)	0	10	0	10	20
River recreation area (square km)	0	0	0	0	20
Reservoir storage (100,000 acre feet)	10	0	0	0	0
Annuitized project costs ($2018 thousands/yr)	1.3	0	1.3	0	10
Breach Damage Potential	0	0	0	0	5
Number of Properties Impacted	5	5	5	5	0
Annual Electricity Generation (GWh/yr)*	10	10	10	10	0
CO2 Emissions Reduction (kilotonne/yr)	20	20	20	20	0
TOTAL	46	45	36	45	55

West Enfield Dam

FERC license expires: May 31, 2024

2 Horizontal pit Kaplan turbines (13 MW)
Run-of-river operation
Eel ladder

Vertical slot fishway (upstream)

1894 Construction: rock-filled crib
1988 Replaced with current dam
2014 Purchased by Brookfield
2019 FERC pre-application document (PAD) filed

West Enfield Dam FERC No. P-2600 : RAW DECISION MATRIX

Decision Criteria	Keep and Maintain Dam	Improve Fish Passage	Improve Hydropower Capacity	Improve Hydro AND Fish Passage	Remove Dam
Sea-run fish habitat area (100 square m)	24,200	55,480	24,200	55,480	86,750
River recreation area (square km)	12	12	12	12	12-26
Reservoir storage (100,000 acre feet)	0	0	0	0	0
Annuitized project costs ($2018 thousands/yr)	949	1,067	949	1,067	179
Breach Damage Potential	2	2	2	2	0
Number of Properties Impacted	0	0	0	0	5
Annual Electricity Generation (GWh/yr)*	73	73	73	73	0
CO2 Emissions Reduction (kilotonne/yr)	10	10	10	10	0
Indigenous Lifeways	1.0	4.0	1.5	4.0	5.0
Industrial Historical Value	3.0	3.0	3.0	2.7	2.3
Community Identity	3.0	3.0	2.0	2.5	3.0
Aesthetic Value	1.8	3.3	2.4	2.3	4.2
Public Health	2.2	3.8	3.0	3.3	4.3
Social and Environmental Justice	1.0	4.5	1.5	4.0	5.0

*1 GWh = 1000 MWh, so to convert from GWh to MWh, multiply the value by 1,000. To convert from MWh to GWh, divide by 1,000.

Prepared by Sharon Klein, Kaitlyn Raffier and Emma Fox for a Future of Dams Multi-Criteria Decision Analysis Workshop, October 2019

Medway Dam

FERC license expires: 2029

1922 Original construction
1979 Original FERC license
2009 Ownership transferred to Black Bear Hydro (now Brookfield)

5 hydroelectric generating units (3.44 MW)

Run-of-river operation

Eel passage up and downstream

Low-Impact-Hydro (LIHI)-certified until June 2020

Medway Dam FERC No. P-2666 : RAW DECISION MATRIX

Decision Criteria	Keep and Maintain Dam	Improve Fish Passage	Improve Hydropower Capacity	Improve Hydro AND Fish Passage	Remove Dam
Sea-run fish habitat area (100 square m)	0	0	0	0	0
River recreation area (square km)	0	0	0	0	0 - 15
Reservoir storage (100,000 acre feet)	0	0	0	0	0
Annuitized project costs ($2018 thousands/yr)	246	279	1,148	1,181	160
Breach Damage Potential	2	2	2	2	0
Number of Properties Impacted	0	0	0	0	11
Annual Electricity Generation (GWh/yr)*	28	28	48	48	0
CO2 Emissions Reduction (kilotonne/yr)	5.1	8.7	5.1	8.7	0
Indigenous Lifeways	1.3	4.0	1.5	3.5	5.0
Industrial Historical Value	2.5	1.5	2.5	1.5	2.5
Community Identity	2.3	3.0	1.5	2.5	4.0
Aesthetic Value	1.4	3.3	1.7	3.0	4.8
Public Health	1.8	4.5	2.0	4.0	4.4
Social and Environmental Justice	1.0	4.0	1.5	4.0	5.0

*1 GWh = 1000 MWh, so to convert from GWh to MWh, multiply the value by 1,000. To convert from MWh to GWh, divide by 1,000.

Prepared by Sharon Klein, Kaitlyn Raffier and Emma Fox for a Future of Dams Multi-Criteria Decision Analysis Workshop, October 2019

East Millinocket Dam

FERC license expires: 2026

6 horizontal Francis turbines (7 MW)

No fish passage

Store-and-release operation in tandem with Ripogenus

1906 Construction: concrete & earth-filled gravity

2001 Acquired by Brookfield

East Millinocket Dam (Penobscot Mills Project) FERC No. P-2458

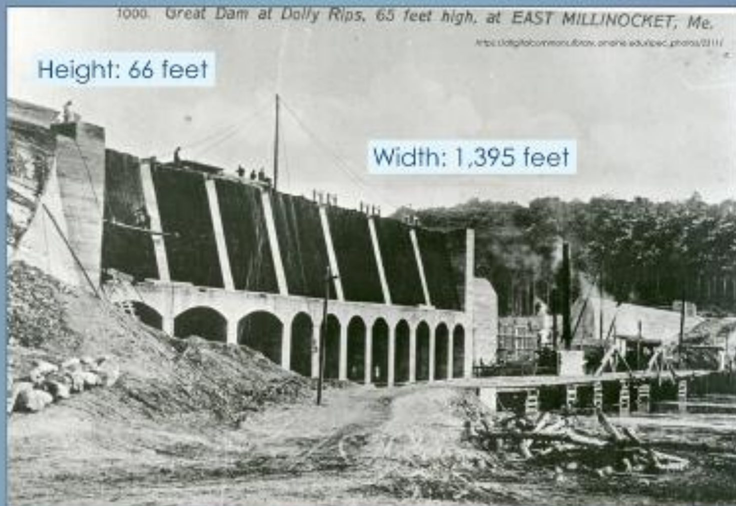
Decision Criteria	Keep and Maintain Dam	Improve Fish Passage	Improve Hydropower Capacity	Improve Hydro AND Fish Passage	Remove Dam
Sea-run fish habitat area (100 square m)	0	0-18	0	0-18	4-37
River recreation area (square km)	0	0	0	0	0-16
Reservoir storage (100,000 acre feet)	0	0	0	0	0
Annuitized project costs ($2018 thousands/yr)	406	471	1,897	1,962	168
Breach Damage Potential	0	0	0	0	0
Number of Properties Impacted	0	0	0	0	0
Annual Electricity Generation (GWh/yr)*	38	38	60	60	0
CO_2 Emissions Reduction (kilotonne/yr)	6.8	6.8	10.8	10.8	0
Indigenous Lifeways	1.0	4.5	2.0	3.9	5.0
Industrial Historical Value	3.3	5.0	5.0	5.0	2.7
Community Identity	2.5	5.0	5.0	5.0	3.0
Aesthetic Value	2.7	5.0	5.0	5.0	3.3
Public Health	2.7	3.5	3.5	3.5	3.7
Social and Environmental Justice	1.0	4.4	2.0	3.8	5.0

*1 GWh = 1000 MWh, so to convert from GWh to MWh, multiply the value by 1,000. To convert from MWh to GWh, divide by 1,000.

Prepared by Sharon Klein, Kaitlyn Raffier and Emma Fox for a Future of Dams Multi-Criteria Decision Analysis Workshop, October 2019

Dolby Dam

FERC license expires: 2026



1907 Construction: concrete & earth-filled

2001 Acquired by Brookfield

3 horizontal Francis, 2 tube inclined, 1 vertical Kaplan turbines (21 MW)

No fish passage

Store-and-release operation in tandem with Ripogenus

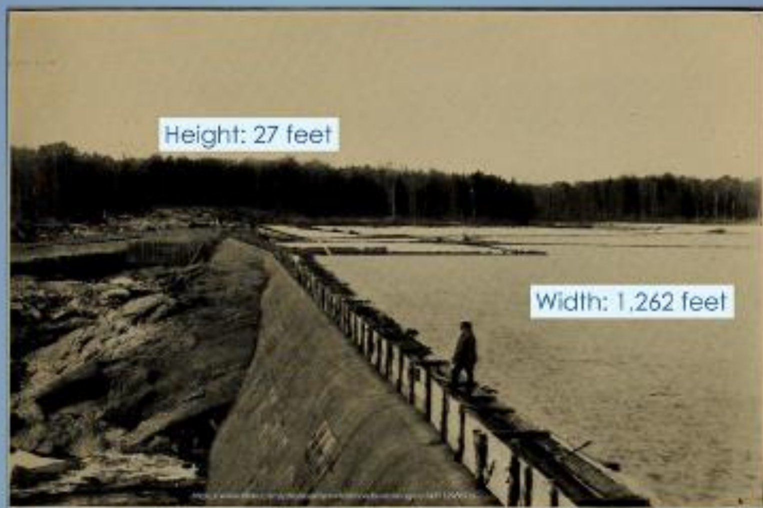
Dolby Dam (Penobscot Mills Project) FERC No. P-2458

Decision Criteria	Keep and Maintain Dam	Improve Fish Passage	Improve Hydropower Capacity	Improve Hydro AND Fish Passage	Remove Dam
Sea-run fish habitat area (100 square m)	0	0-295	0	0-295	0-590
River recreation area (square km)	0	0	0	0	0 - 16
Reservoir storage (100,000 acre feet)	0.3	0.3	0.3	0.3	0.00
Annuitized project costs ($2018 thousands/yr)	1,229	1,415	1,229	1,415	319
Breach Damage Potential	1	1	1	1	0
Number of Properties Impacted	0	0	0	0	25
Annual Electricity Generation (GWh/yr)*	98	98	98	98	0
CO2 Emissions Reduction (kilotonne/yr)	12.9	12.9	12.9	12.9	0
Indigenous Lifeways	1.5	5.0	3.0	4.0	4.5
Industrial Historical Value	3.0	3.0	3.5	3.5	3.0
Community Identity	2.7	4.0	3.5	4.0	3.0
Aesthetic Value	2.8	4.5	4.0	4.5	3.3
Public Health	2.3	3.7	3.0	3.3	4.3
Social and Environmental Justice	1.5	4.0	3.0	3.0	4.5

*1 GWh = 1000 MWh, so to convert from GWh to MWh, multiply the value by 1,000. To convert from MWh to GWh, divide by 1,000.

Millinocket/Quakish Dam

FERC license expires: 2026



1900 Construction: concrete & stone gravity dam

2001 Acquired by Brookfield

8 horizontal Francis turbines (36 MW)

No fish passage

Store-and-release operation in tandem with Ripogenus

Millinocket/Quakish Dam (Penobscot Mills Project) FERC No. P-2458 : RAW DECISION MATRIX

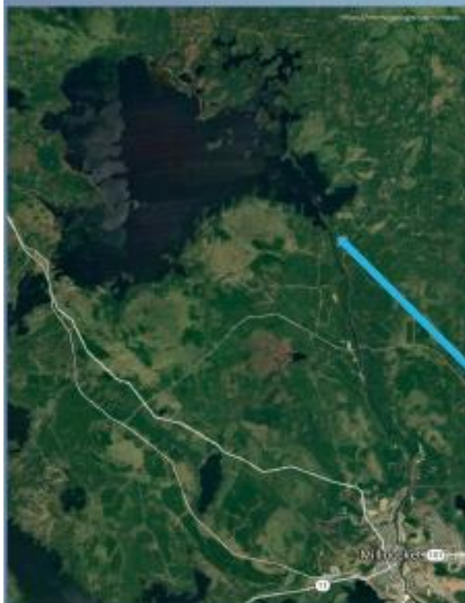
Decision Criteria	Keep and Maintain Dam	Improve Fish Passage	Improve Hydropower Capacity	Improve Hydro AND Fish Passage	Remove Dam
Sea-run fish habitat area (100 square m)	0	0-6	0	0-6	0-12
River recreation area (square km)	0	0	0	0	0 -16
Reservoir storage (100,000 acre feet)	0.1	0.1	0.1	0.1	0.00
Annuitized project costs ($2018 thousands/yr)	1,657	1,970	1,657	1,970	215
Breach Damage Potential	0	0	0	0	0
Number of Properties Impacted	0	0	0	0	9
Annual Electricity Generation (GWh/yr)*	203	203	203	203	0
CO2 Emissions Reduction (kilotonne/yr)	26.7	26.7	26.7	26.7	0
Indigenous Lifeways	1.0	4.5	2.0	3.9	5.0
Industrial Historical Value	2.5	2.9	3.5	3.1	3.5
Community Identity	1.0	3.8	3.0	3.6	5.0
Aesthetic Value	2.5	3.2	3.3	3.6	3.5
Public Health	2.5	4.0	4.0	4.0	4.5
Social and Environmental Justice	1.0	4.4	2.0	3.8	5.0

*1 GWh = 1000 MWh, so to convert from GWh to MWh, multiply the value by 1,000. To convert from MWh to GWh, divide by 1,000.

Prepared by Sharon Klein, Kaitlyn Raffier and Emma Fox for a Future of Dams Multi-Criteria Decision Analysis Workshop, October 2019

Millinocket Lake Dam

FERC license expires: 2026



1883 Construction: concrete & earth-filled
2001 Acquired by Brookfield
Non-powered (0 MW), with pump station
No fish passage
Store-and-release operation in tandem with Ripogenus

Millinocket Lake Dam (Penobscot Mills Project) FERC No. P-2458

Decision Criteria	Keep and Maintain Dam	Improve Fish Passage	Improve Hydropower Capacity	Improve Hydro AND Fish Passage	Remove Dam
Sea-run fish habitat area (100 square m)	0	0-275	0	0-275	0-550
River recreation area (square km)	0	0	0	0	0
Reservoir storage (100,000 acre feet)	0.4	0.4	0.4	0.4	0
Annuitized project costs ($2018 thousands/yr)	1	7	102	108	62
Breach Damage Potential	1	1	1	1	0
Number of Properties Impacted	0	0	0	0	119
Annual Electricity Generation (GWh/yr)*	0	0	1	1	0
CO2 Emissions Reduction (kilotonne/yr)	0	0	0.1	0.1	0
Indigenous Lifeways	1.0	4.5	2.0	3.9	5.0
Industrial Historical Value	2.0	2.9	3.5	3.1	3.5
Community Identity	1.0	3.8	3.0	3.6	5.0
Aesthetic Value	2.5	3.4	3.2	3.6	3.5
Public Health	2.5	4.0	4.0	4.0	4.5
Social and Environmental Justice	1.0	4.4	2.0	3.8	5.0

*1 GWh = 1000 MWh, so to convert from GWh to MWh, multiply the value by 1,000. To convert from MWh to GWh, divide by 1,000.

Prepared by Sharon Klein, Kaitlyn Raffier and Emma Fox for a Future of Dams Multi-Criteria Decision Analysis Workshop, October 2019

North Twin Dam

FERC license expires: 2026

1846 Construction: earth-filled gravity

2001 Acquired by Brookfield

2 vertical Francis, 1 vertical Kaplan turbines (7 MW)

No fish passage

Store-and-release operation in tandem with Ripogenus

North Twin Dam (Penobscot Mills Project) FERC No. P-2458

Decision Criteria	Keep and Maintain Dam	Improve Fish Passage	Improve Hydropower Capacity	Improve Hydro AND Fish Passage	Remove Dam
Sea-run fish habitat area (100 square m)	0	0-826	0	0-826	0-1652
River recreation area (square km)	2	2	2	2	2 - 17
Reservoir storage (100,000 acre feet)	0.2	0.2	0.2	0.2	0.00
Annuitized project costs ($2018 thousands/yr)	403	467	1,880	1,945	212
Breach Damage Potential	1	1	1	1	0
Number of Properties Impacted	0	0	0	0	589
Annual Electricity Generation (GWh/yr)*	47	47	75	75	0
CO2 Emissions Reduction (kilotonne/yr)	8.5	8.5	13.4	13.4	0
Indigenous Lifeways	1.5	5.0	2.0	4.0	4.5
Industrial Historical Value	3.3	2.0	4.0	3.0	2.7
Community Identity	3.0	4.0	3.0	4.0	3.0
Aesthetic Value	1.7	4.0	3.0	3.0	4.3
Public Health	2.5	4.0	4.0	3.5	4.5
Social and Environmental Justice	1.0	5.0	2.0	4.0	5.0

*1 GWh = 1000 MWh, so to convert from GWh to MWh, multiply the value by 1,000. To convert from MWh to GWh, divide by 1,000.

Prepared by Sharon Klein, Kaitlyn Raffier and Emma Fox for a Future of Dams Multi-Criteria Decision Analysis Workshop, October 2019

Ripogenus Dam

FERC license expires: 2026

1916 Original construction

1996 Great Northern Paper (now Brookfield) listed as owner in FERC license

3 hydroelectric generating units (38 MW)

No fish passage

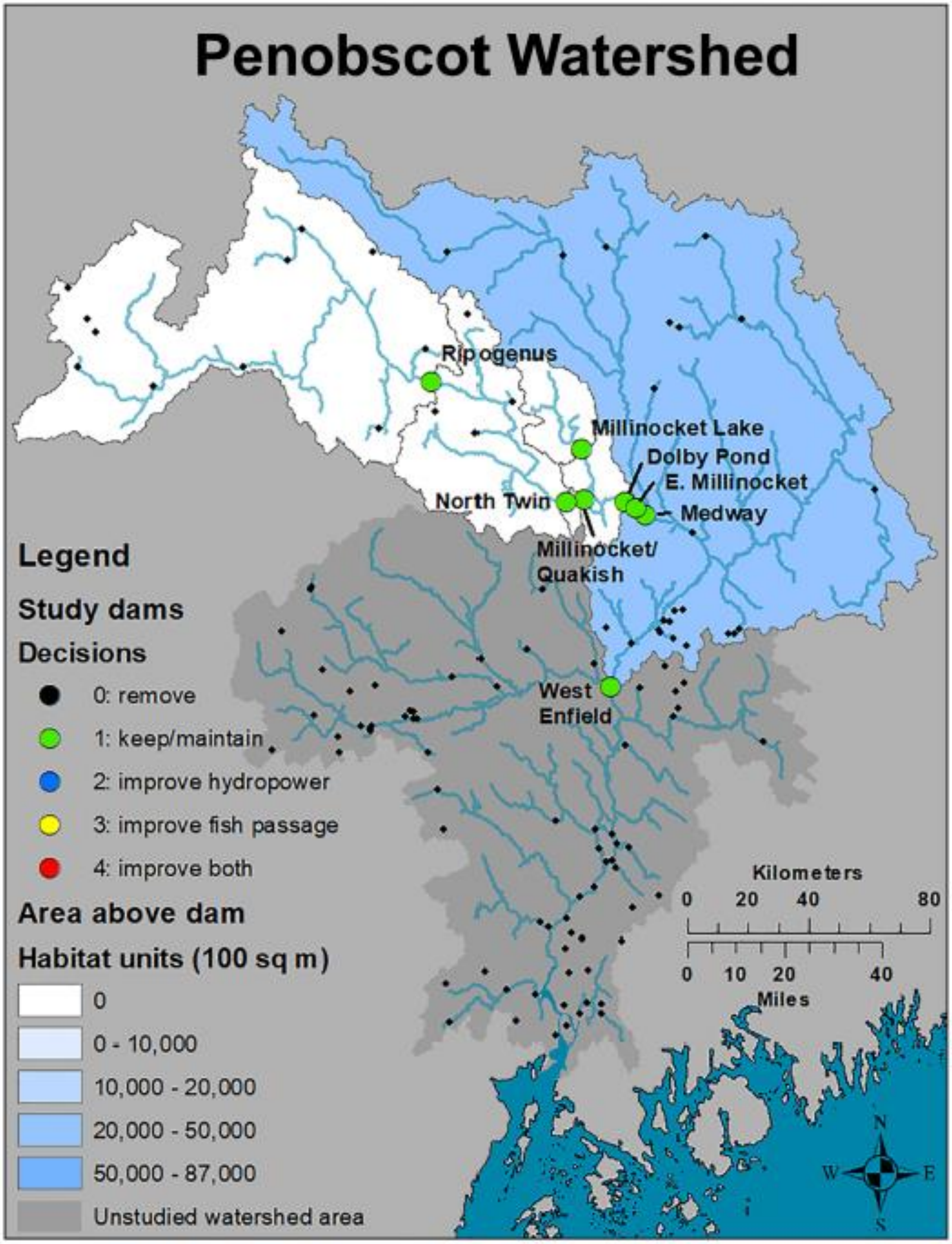
Store-and-release operation in tandem with Penobscot Mills Project

Ripogenus FERC No. P-2572 : RAW DECISION MATRIX

Decision Criteria	Keep and Maintain Dam	Improve Fish Passage	Improve Hydropower Capacity	Improve Hydro AND Fish Passage	Remove Dam
Sea-run fish habitat area (100 square m)	0	0-2480	0	0-2480	0-4961
River recreation area (square km)	2	2	2	2	2 - 17
Reservoir storage (100,000 acre feet)	14	14	14	14	0
Annuitized project costs ($2018 thousands/yr)	747	1,072	3,487	3,813	724
Breach Damage Potential	2	2	2	2	0
Number of Properties Impacted	0	0	0	0	43
Annual Electricity Generation (GWh/yr)*	234	234	281	281	0
CO2 Emissions Reduction (kilotonne/yr)	30.7	30.7	36.8	36.8	0
Indigenous Lifeways	1.0	4.5	2.0	3.9	5.0
Industrial Historical Value	2.0	2.9	3.0	3.1	3.5
Community Identity	1.0	3.8	3.0	3.6	5.0
Aesthetic Value	1.5	3.4	3.2	3.6	4.5
Public Health	2.5	4.0	4.0	4.0	4.0
Social and Environmental Justice	1.0	4.4	2.0	3.8	5.0

*1 GWh = 1000 MWh, so to convert from GWh to MWh, multiply the value by 1,000. To convert from MWh to GWh, divide by 1,000.

Prepared by Sharon Klein, Kaitlyn Raffier and Emma Fox for a Future of Dams Multi-Criteria Decision Analysis Workshop, October 2019



Poster prepared by Sam Roy, with input from Sharon Klein and Emma Fox, for a Future of Dams Multi-Criteria Decision Analysis Workshop, October 2013

APPENDIX O: IRB APPROVAL AND CONSENT FORMS

The FOD Institutional Review Board (IRB) Approval Letter (p.413 – 414) is for joint IRB with University of Rhode Island, University of Maine, University of New Hampshire, Rhode Island School of Design, Keene State College, and University of Southern Maine. I include the consent form (p. 415 – 417) and MCDA workshop protocol addendum (p. 418 – 420) relevant to the FOD IRB (stakeholder interview protocol can be found in Appendix J, along with the interview codebook). I also include herein the first page of the approved joint Penobscot Nation- University of Maine IRB application (p. 421) and consent form (p. 422 – 424) for MCDA workshop, because our work with Penobscot Nation participants fell under a different research protocol.

THE
UNIVERSITY
OF RHODE ISLAND
DIVISION OF RESEARCH
AND ECONOMIC
DEVELOPMENT

THINK BIG WE DO™

OFFICE OF RESEARCH INTEGRITY
70 Lower College Road, Suite 2, Kingston, RI 02881 USA
p: 401.874.4328 f: 401.874.4814 uri.edu/research/tro/offices/researchintegrity

FWA:	00003132
IRB:	00000599
DATE:	July 9, 2015
TO:	Caroline Druschke, PhD
FROM:	University of Rhode Island IRB
STUDY TITLE:	Strengthening the Scientific Basis for Decision Making about Dams
IRB REFERENCE #:	778925-1
LOCAL REFERENCE #:	HU1516-003
SUBMISSION TYPE:	New Project
ACTION:	APPROVED
EFFECTIVE DATE:	July 9, 2015
EXPIRATION DATE:	July 8, 2016
REVIEW TYPE:	Expedited Review
REVIEW CATEGORY:	Expedited review category # *6 & 7*

Thank you for your submission of New Project materials for this research study. The University of Rhode Island IRB has APPROVED your submission. This approval is based on an appropriate risk/benefit ratio and a study design wherein the risks have been minimized. All research must be conducted in accordance with this approved submission.

This submission has received Expedited Review based on the applicable federal regulation 45 CFR 46 and 21 CFR 50 & 56.

Please note that any revision to previously approved materials must be approved by this office prior to initiation. Please use the appropriate revision forms for this procedure.

All SERIOUS and UNEXPECTED adverse events must be reported to this office. Please use the appropriate **Appendix S - Event Reporting** for this procedure. All FDA and sponsor reporting requirements must be followed.

Please report all NON-COMPLIANCE issues or COMPLAINTS regarding this study to this office. Please note that all research records must be retained for a minimum of five years after the project ends.

Based on the risks, this project requires Continuing Review by this office by July 8, 2016. Please use the **CONTINUING REVIEW FORM** for this procedure.

If you have any general questions, please contact us by email at researchintegrity@ds.uri.edu. For study related questions, please contact us via **project mail through IRBNet**. Please include your study title and reference number in all correspondence with this office.

Please remember that informed consent is a process beginning with a description of the study and insurance of participant understanding followed by a signed consent form. Informed consent must continue throughout the study via a dialogue between the researcher and research participant. Federal regulations require each participant receive a copy of the signed consent document unless the signature requirement has been waived by the IRB.

Andrea Rusnock, Ph.D
IRB Chair

THE UNIVERSITY OF RHODE ISLAND
COLLEGE OF THE ENVIRONMENT AND LIFE SCIENCES

Department of Natural Resources Science
Coastal Institute, 1 Greenhouse Road
Kingston, RI 02881 USA
http://web.uri.edu/nrs/

STRENGTHENING THE SCIENTIFIC BASIS FOR DECISION MAKING ABOUT DAMS

CONSENT FORM FOR RESEARCH

You have been asked to participate in a research project described below. The researcher will explain the project to you in detail. You should feel free to ask questions. If you have more questions later, Dr. Todd Guilfoos (401) 874-4398, the person mainly responsible for this study, will discuss them with you. You must be at least 18 years old to participate in this research project.

Description of the project:
This study examines decision making preferences and processes about dams. We hope to learn about public preferences for ecosystem services from dams, common arguments for and against dams, and how collaborative decision processes impact decisions about dam removal, rehabilitation, and upgrading.

What will be done:
You have been invited to participate in the following research components (*check one or more*):

___ In the **interview and/or stakeholder survey** portion of this study, you will be asked a series of questions about dams, decision making, and collaboration. Interviews are expected to last from 30 to 120 minutes, while surveys will take approximately 20 minutes to complete. Interview participants may be asked for follow-up interviews.

___ In the **lab experiment**, you will be presented with a sequence of decisions that provide you an opportunity to make money. Your earnings will be affected by your decisions and the decisions of others. The process should take not more than two hours.

___ In the **choice experiment**, you will be asked to complete either an internet-based survey or an in-person workshop. Survey participants will answer a series of questions about valuing ecosystem services related to dams. Workshop participants will be asked to complete complex decision making tasks related to valuation. Surveys will take approximately 20 minues, while workshops will take not more than two hours.

___ In the **charrette**, you will be asked to provide feedback about several computer models and take on the role of a particular type of stakeholder to work through the tradeoffs related to particular dam decisions. These two workshops are expected to last approximately 6 hours each.

In the **role-play simulation**, you will be asked to participate in two workshops and to fill out a survey/concept map before the first workshop (either online or in-person) and after the second workshop. Each survey/concept map is expected to take 20 minutes. During the workshops, participants will be asked to interact with and provide feedback about a computer model and decision scenario and participate in a role-play in which they take on the role of a particular stakeholder to negotiate a dam decision. Each workshop is expected to last 4 hours, including time needed to fill out the survey/concept map. Workshop participants may be asked for follow-up interviews.

IRB NUMBER: HU1516-003
IRB APPROVAL DATE: December 22, 2018
IRB EXPIRATION DATE: July 8, 2019

✓ In the **MCDA workshop**, you will be asked to fill out a pre/post-survey about your preferences for particular dam decision criteria, expected to take 60 minutes. Participants will be asked to interact with a computer model and rate a series of criteria, as well as discuss the experience and provide feedback about the model and results. The workshop is expected to last 8 hours, including time needed to fill out a post-survey. Workshop participants may be asked for follow-up interviews.

___ In the **evaluation discussions**, you will be invited to discuss your vision for decision support evaluation, and the metrics by which you gauge success in both decision process and outcomes. These discussions may take place in person or over Zoom conference calling software, and are expected to last 60 to 90 minutes each. Evaluation discussion participants will be asked to participante in follow-up interviews.

Risks or discomfort:
It is unlikely that you will incur any risks or will experience any discomfort as a result of participating in this study.

Benefits of this study:
Although there may be no direct benefit to you from participation in this study, the researchers may learn more about how people use science to make decisions about dams and about how collaboration impacts decision making, resulting in better decision making about dams.

Confidentiality:
Your part in this study is confidential. None of the information will identify you by name. Your name will not be included in the transcript of interviews, workshops, evaluation discussions, concept maps, role-plays, or charrettes. Audio recordings will be erased after they are transcribed. Signed consent forms will be kept in the investigator's locked cabinet, separate from any transcripts. For the experiments, decisions will be linked by a subject number assigned to you by the researcher. This subject number will never be linked to anything which can identify you. Other participants in the experiment will not be able to attribute your decisions to you personally, and they will not know how much you earn. At the end of the experiment, you will have to sign for the amount of your earnings. This form will not contain your subject number, and will not be linked with your decision data.

Decision to quit at any time:
The decision to take part in this study is up to you. You do not have to participate. If you decide to take part in the study, you may quit at any time. Whatever you decide will in no way penalize you. If you wish to quit, simply inform the researcher of your decision.

Rights and complaints:
If you are not satisfied with the way this study is performed, you may discuss your complaints with Dr. Guilfoos or with staff members at the office of the Vice President of Research and Economic Development (401-874-4328), anonymously, if you choose. In addition, if you have questions about your rights as a research participant, you may contact the office of the Vice President of Research and Economic Development, 70 Lower College Road, Suite 2, University of Rhode Island, Kingston, RI, telephone: 401-874-4328.

You have read this Consent Form. Your questions have been answered. Your signature on this form means that you understand the information and you agree to participate in this study.

______________________	______________________
Signature of Participant	Signature of Researcher
	Emma Fox
______________________	______________________
Typed/printed Name	Typed/printed name
	9/23/2019
______________	______________
Date	Date

Please sign both consent forms, keeping one for yourself

___ I agree to let the researcher **audio record** the interview/role-play simulation. Audio recordings will be held until they are transcribed, at which point they will be destroyed. If you agree, please sign below:

__________________________ Signature   __________________ Date

THE UNIVERSITY OF RHODE ISLAND

IRB NUMBER:	HU1516-003
IRB APPROVAL DATE:	December 22, 2018
IRB EXPIRATION DATE:	July 8, 2019

FOD (URI APPROVED) MCDA Addendum: surveys/workshops protocol

Research Design:

Participatory workshops are a way to engage decision makers using Multi-Criteria Decision Analysis (MCDA), a structured decision making framework, in a deliberative setting. The participatory MCDA workshops will be preceded by individual web-based stakeholder surveys taken prior to arriving at the workshops, and followed by an individual web-based post-survey. A web-based MCDA tool will integrate decision criteria information from stakeholder interviews in a model that elicits preferences from stakeholders during the workshops and calculates decision scores based on these preferences. Workshop participants will interact with the web-based MCDA tool both individually and as a group, under researcher guidance. MCDA tool interaction will be followed by pair and then group discussion of results and feedback. Participants will be dam stakeholders, people with prior experience and/or knowledge of dam decisions – most of whom have already been involved in the Future of Dams project through interviews and other research activities. The primary purpose of the survey instrument is assessment and evaluation of the MCDA workshop. Key points of evaluation:

1) Individual stakeholder baseline for priority decision alternatives and criteria, overall dam/water resource management objectives

2) Differences between individual preferences before and after intervention using MCDA tool

3) Differences between individual preferences before and after group deliberation over criteria for MCDA tool

4) Outcomes in group decision-making processes. Was the process manageable? Was consensus reached? Is the outcome equitable and environmentally sustainable?

5) Decision process. Did the process make sense? Did the activity facilitate trust-building? Did it foster collaboration or enhance capacity for decision making?

6) Effectiveness of the facilitators. Was the activity and facilitation transparent? Was the guidance adaptive?

As a way to engage participants in co-creating evaluation metrics (see addendum B), evaluation discussions will be held prior to the MCDA workshops to identify stakeholder visions for decision support and definitions for success in decision processes and outcomes. These evaluation discussions will aid in the comparison of participatory decision support with PSDS or role-play simulations/charrettes (see addendum F) and MCDA workshops.

Procedures:

Because of our unique opportunity to compare group participatory MCDA and PSDS (role-play simulation/charrette), between 20- 40 stakeholders will be invited to participate in evaluation discussions and/or MCDA workshops. In the evaluation discussion, stakeholders will be invited to share their vision for decision support evaluation and the metrics by which they gauge success in decision process and outcomes. Evaluation discussions may take place in person or over Zoom conference calling software, and are expected to last 60 to 90 minutes each. Evaluation discussion participants may be asked to participate in follow-up interviews.

Two rounds of participatory MCDA workshops will bring together stakeholders in Maine's Penobscot and Union River watersheds. Participants will include a diverse group of stakeholders involved in making decisions about dams. Prior to the workshop, participants will receive and complete a pre-survey (designed in Google Forms) of stakeholder preferences about sustainability criteria relating to dams, which participants will complete individually.

A web-based MCDA tool will elicit stakeholder preferences and facilitate consideration of dam decision alternatives during the workshop. Workshops will start with a round robin of introductions and then a brief introductory presentation of how MCDA works, along with a set of illustrative examples. Participants will access a web app that houses our MCDA tool, read the directions individually (facilitators will answer questions), and then move through each of the decision alternative tabs, rating decision criteria as they go. Participants will pair-share their MCDA results (a ranking and quantitative score for a set of decision alternatives based on their own ranking), after which the entire participant group will discuss the experience. Participants will then be divided into subgroups of 4-10 to work with an individual facilitator and asked to again access the web app with the MCDA tool, this time moving through each of the decision alternative tabs as a group, deliberating over criteria ratings (and ideally coming to consensus). Finally, the entire participant group will discuss the MCDA tool results and compare/contrast the individual and group experiences with the tool.

Facilitators will ask for participant feedback, including: 1) what model components worked well or were challenging, 2) whether their results were believable, made sense, and/or were what they expected, and 3) what might be done to improve the web app and workshop framework to meet stakeholder needs. During the workshop, discussions will be audio recorded, and researchers will take a written record of participant feedback and questions. The workshop will conclude with a post-survey. Workshop participants may be invited to interview as a secondary form of follow-up. The results of in-depth interviews conducted before the workshops (addendum B) and the pre/post survey will be analyzed to assess individuals' changing preferences and knowledge about criteria in watershed-scale dam decision making. Results from individual MCDA model results will be compared with group model results and pre/post survey results. The evaluation discussion participants will be invited to interview individually as follow-up to discuss preferences for the evaluative rubric based on their experience in the MCDA or PSDS workshop (see addendum F). Due to the lengthy nature of engagement in MCDA workshops, and evaluation discussions, and potentially follow-up interviews, we expect the evaluation discussion participant group to be much smaller, no more than 10 participants.

Risks and anticipated benefits:

There is minimal risk to the participants. Personal information of the participants will be kept confidential. On the other hand, they are likely to benefit from knowledge coproduction and knowledge dissemination. Benefits include knowledge acquisition about dam decision criteria.

# of participants:

Up to 30 participants can be included in the workshops, which will require 8 hours. Food and beverages will be provided for participants during breaks.

Time commitment:

All participants are expected to spend 6 - 8 hours in the workshop (including post-survey) plus 1 hour to complete the pre-survey, for a total of 7- 9 hours. Workshop participants also participating in evaluation discussions are expected to spend 1 to 1.5 hours in each of two discussions for a total of up to 11.5 hours on MCDA-related activities.

Knowledge gained from the intervention

Knowledge gained by the workshops will be used to revise the web-based MCDA decision support tool to be made available publicly to inform other efforts aimed at improving local decisions about dams. Knowledge gained from the evaluation discussions will be used to build a co-created rubric to evaluate and compare the MCDA and PSDS (role-play simulation/charrette) models, decision-making processes, and outcomes. This co-created rubric will be made available publicly to help guide participatory process and decision support considerations in the future.

Information on Confidentiality:

Portions of the MCDA workshops may be recorded and transcribed. Electronic copies of original audio files and transcripts will be kept on a password-protected Google drive and archived in a central data repository for the project, such as UNH Data Discovery Center, shared only with other investigators listed on the IRB approval. Data and electronic recordings will be retained for three years after the completion of the project and then destroyed. Researchers will explain the purpose of the workshop and survey, and provide a consent form to all participants on the day of the workshop that includes a check box to offer permission to record the discussions therein. Transcription will be conducted by TranscribeMe!, an online transcription company that specializes in academic transcriptions and adheres to the standards for the protection of human subjects, including deleting files once they are transcribed and maintaining confidentiality.

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APPLICATION COVER PAGE

- ***KEEP THIS PAGE AS ONE PAGE – DO NOT CHANGE MARGINS/FONTS!!!!!!!!!***
- ***PLEASE SUBMIT THIS PAGE AS WORD DOCUMENT***

APPLICATION FOR APPROVAL OF RESEARCH WITH HUMAN SUBJECTS
Protection of Human Subjects Review Board, 400 Corbett Hall

PRINCIPAL INVESTIGATOR: Tyler Quiring EMAIL: tyler.quiring@maine.edu
CO-INVESTIGATORS: Bridie McGreavy (bridie.mcgreavy@maine.edu); Darren Ranco (darren.ranco@maine.edu); Jan Paul (Jan.Paul@penobscotnation.org); Angie Reed (angie.reed@penobscotnation.org); John Banks (john.banks@penobscotnation.org); Nolan Altvater (nolan.altvater@maine.edu); Brawley Benson (brawley.benson@maine.edu); Kaitlyn Raffier (kaitlyn.raffier@maine.edu); Emma Fox (emma.fox@maine.edu); Natallia Leuchanka (nhe4@wildcats.unh.edu); Sharon Klein (sharon.klein@maine.edu); Catherine Ashcraft (Catherine.Ashcraft@unh.edu)
FACULTY SPONSOR: Bridie McGreavy EMAIL: bridie.mcgreavy@maine.edu
TITLE OF PROJECT: Community-engaged decolonizing research for collaborative decision making about dams and river restoration
START DATE: ~~December 6, 2018~~ 1/8/2019 PI DEPARTMENT: Communication & Journalism
FUNDING AGENCY (if any): National Science Foundation

STATUS OF PI: FACULTY/STAFF/GRADUATE/UNDERGRADUATE G (F,S,G,U)

1. If PI is a student, is this research to be performed:

☐ for an honors thesis/senior thesis/capstone? ☐ for a master's thesis?
X for a doctoral dissertation? ☐ for a course project?
☐ other (specify)

2. Does this application modify a previously approved project? N (Y/N). If yes, please give assigned number (if known) of previously approved project:

3. Is an expedited review requested? Y (Y/N).

Submitting the application indicates the principal investigator's agreement to abide by the responsibilities outlined in Section I.E. of the Policies and Procedures for the Protection of Human Subjects.

Faculty Sponsors are responsible for oversight of research conducted by their students. The Faculty Sponsor ensures that he/she has read the application and that the conduct of such research will be in accordance with the University of Maine's Policies and Procedures for the Protection of Human Subjects of Research. REMINDER: if the principal investigator is an undergraduate student, the Faculty Sponsor MUST submit the IRB application.

Email this cover page and complete application to UMRIC@maine.edu

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FOR IRB USE ONLY Application # 2018-11-10 Review (F/E): E
ACTION TAKEN:

X Judged Exempt; category 2 Modifications required? Y Accepted (date) 1/8/2019
☐ Approved as submitted. Date of next review: by Degree of Risk:
☐ Approved pending modifications. Date of next review: by Degree of Risk:
Modifications accepted (date):
☐ Not approved (see attached statement)
☐ Judged not research with human subjects

FINAL APPROVAL TO BEGIN 1/8/2019
Date

01/2017

Informed Consent Statement and Agreement Worksheet:

Participatory MCDA "Dam Decision Support Workshop"

Our team would like to work with you on research about your relationship to the Penobscot River and dams coming up for relicensing through the Federal Energy Regulatory Commission (FERC) within the next 10 years. This research is being conducted as a collaboration between researchers from the Universities of Maine. We are working together to both improve the forms of decision support available to dam decision makers and to improve the participatory processes where those tools are used. We will explain our research to you in detail as it currently stands, but please feel free to offer guidance and ask questions.

What we will ask you to do:

If you agree, we would like to invite you to participate in a participatory Multi-Criteria Decision Analysis (MCDA) workshop to discuss a set of dams in the Penobscot River with other people like you who have some vested interest in a particular dam or in each of the dams. We welcome your thoughts about how best suit your needs. The MCDA workshop is expected to take 6 – 8 hours and may be audio recorded with your permission. We will provide food, beverage, and parking at no cost to you.

For the **MCDA "Dam Decision Support" workshop**, you will be asked to:

- Fill out a pre-survey prior to attending to share your preferences about different aspects of dams in general, as well as a set of dams in particular (West Enfield Dam, Medway Dam, Penobscot Mills Project, and Ripogenus Dam). The pre-survey may take up to 1 hour.
- Use a Dam Decision Support Tool (a web-based MCDA program) prior to attending to get a feel for the kinds of decisions we will be asking you to work through in a group. This process may take up to 1 hour.
- Participate in an in-person full-day workshop with other people who care about dams coming up for relicensing in the Penobscot River (West Enfield Dam, Medway Dam, Penobscot Mills Project, and Ripogenus Dam).
- Fill out a post-survey before leaving the workshop site to provide feedback about your experience in the workshop.

Risks of this study:

For this study, the most apparent risks you will face as a participant are to your time and convenience. We also realize that relationships between European descendants and Wabanaki people have had a long, complex, and traumatic history, and that this history shapes our university's work with the Penobscot Nation. Because of this history, we have developed research review in partnership with the Penobscot Nation so that we are getting the story right, taking care with how you and your preferences are represented to your Nation and other communities, and exploring what role you may wish to have in research. Please let me know if you have thoughts about this, or if there are other concerns we should be aware of.

Benefits of this study:

The immediate benefits of this research to you include having access to your survey results and MCDA decision support tool output (graphs and tables representing your preference information), which we will provide, and the co-production of knowledge about the Penobscot River. Other benefits we see include contributions to Penobscot Nation cultural and scientific resources, ongoing decision making about the

Penobscot River and dams more generally, participatory decision-making processes, and ethical research collaboration between universities and native tribes. Please let us know if you would like to talk about any of these benefits and if there are other potential benefits that would be important to you.

Confidentiality:

By default, we will preserve your confidentiality by removing personal identifiers from the written and audio records of our conversations. By default, your responses will be kept in confidential form (with personally identifiable information removed) during data generation and processing, and will only be accessible to research personnel and there will be a key linking your name to your responses. This key will be stored on a desktop computer in 111B Norman Smith Hall and backed up to the cloud using Google Drive. The key will be protected using software that provides additional security, and the password will only be known to study personnel. Your responses will be kept until the completion of this study in August 2020. Using the form on this page, you can also choose to have your identity accompany your survey responses and model results (i.e., your data) and to have your data be kept in perpetuity by the Penobscot Nation after August 2020. If you agree to have your participation in the workshop recorded, we will use an external service to prepare a transcript of the recording, which will be only be privately accessible to researchers to maintain confidentiality of all participants. Given the format of the workshop, we cannot guarantee confidentiality of information you share with other participants.

Voluntary:

The decision to take part in this study is up to you. You do not have to participate. If you decide to take part in the study, you may quit at any time. Whatever you decide will in no way penalize you. If you wish to quit, just let us know. You may also skip any portion of the workshop that you do not wish to participate in.

Contact information:

If you have further questions about this study, you may discuss them with: Tyler Quiring (207) 417-5023, tyler.quiring@maine.edu; Emma Fox (203) 331-5565, emma.fox@maine.edu; Sharon Klein (207) 581-3174; or any of the other personnel involved (let us know if you would like their contact information). If you have any questions about your rights as a research participant, please contact the Office of Research Compliance, University of Maine, (207) 581-2657 (or email umric@maine.edu).

***MCDA Participant Agreement (participant completes)*:**

1. Date: ______________________________

2. I want my survey responses to be shared with the Penobscot Nation Cultural and Historic Preservation Department's archives: Yes No
   a. *With my name included:* Yes No
   b. *To be available to other Penobscot tribal citizens in a password protected website:* Yes No

   Comment:

3. I want my survey responses to be shared publicly: Yes No
   a. *With my name included:* Yes No

   Comment:

4. I want my MCDA model output to be shared with the Penobscot Nation Cultural and Historic Preservation Department's archives: Yes No
   a. *With my name included:* Yes No
   b. *To be available to other Penobscot tribal citizens in a password protected website:* Yes No

   Comment:

5. I want my MCDA model output to be shared publicly: Yes No
   a. *With my name included:* Yes No

   Comment:

6. I want to be involved in future planning for this research: Yes No
   Comment:

BIOGRAPHY OF THE AUTHOR

Emma Louise Boissevain Fox graduated *magna cum laude* in 2012 from Saint Michael's College in Colchester, Vermont, from the Honors Program with a Bachelor of Science in Biology. Emma earned her Master of Science degree in Ecology and Environmental Science from the University of Maine in December 2016 before beginning her Ph.D. program, also in Ecology and Environmental Science. As a Ph.D. student Emma won two mentorship awards: (2019) All Maine Women Mentorship, awarded by the All Maine Women Honor Society; and (2018) Outstanding Mentorship for a Student in Sustainability Research, awarded by the Senator George J. Mitchell Center for Sustainability Solutions. Emma was also recognized as a distinguished nominee for the (2019) Edith M. Patch Award, awarded by the Friends of Edith Patch at the University of Maine. Her Ph.D. research was funded by the NSF-EPSCoR Future of Dams Project, a multi-state, multi-institutional project aimed at improving the science behind dam decision making. She is a candidate for the Doctor of Philosophy degree in Ecology and Environmental Sciences from the University of Maine in May 2020.